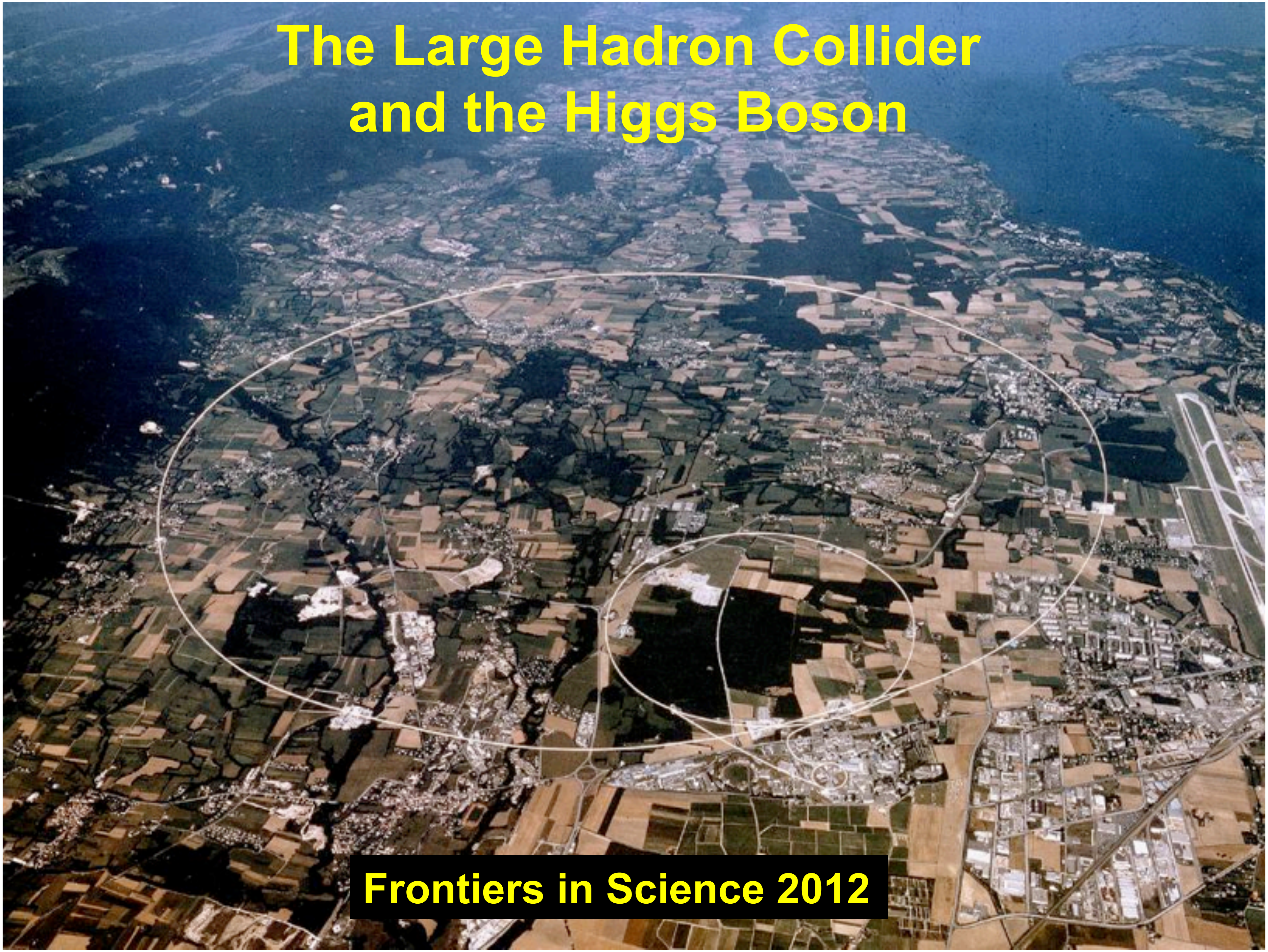
The Large Hadron Collider and the Higgs Boson



Frontiers in Science 2012

High Energy Physics

The Science of Matter, Energy, Space and Time

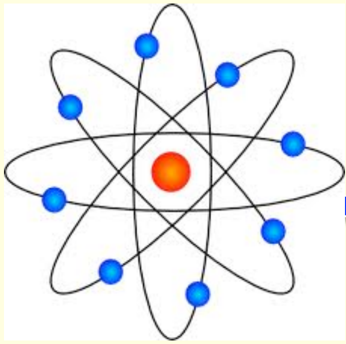
High Energy Physics

The Science of Matter, Energy, Space and Time

Key questions that define the field ==>

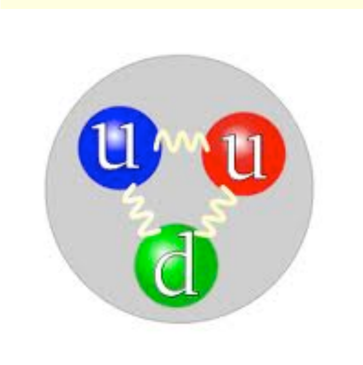
1. Are there undiscovered principles of nature: new symmetries or laws?
2. Why are there so many kinds of particles?
3. Do all the forces become one?
4. What is the origin of mass?
5. Are there extra dimensions of space?
6. What are neutrinos telling us?
7. What is dark matter? How can we make it in the laboratory?
8. How can we solve the mystery of dark energy?
9. What happened to the antimatter?
10. How did the universe come to be?

Brief Introduction to High Energy Physics



Atoms (10^{-10} m – a billionth of an inch) consist of a nucleus surrounded by electrons. Held together by the electric force.

The nucleus (10^{-14} m – a trillionth of an inch) consists of protons and neutrons. Held together by the strong nuclear force.



Protons and neutrons contain quarks ($<10^{-18}$ m).

How many types of quarks? What forces act between them?

Brief Introduction to Forces

Electricity Magnetism Weak Nucl. Strong Nucl. Gravity

Short range forces, significant only inside of the nucleus

Brief Introduction to Forces

Electricity Magnetism Weak Nucl. Strong Nucl. Gravity

$\underbrace{\text{Electricity} \quad \text{Magnetism}}_{\text{Electromagnetism}}$

Short range forces, significant only inside of the nucleus

Brief Introduction to Forces

Electricity Magnetism Weak Nucl. Strong Nucl. Gravity

Short range forces, significant only inside of the nucleus

Electromagnetism	Weak Nucl.	Strong Nucl.	Gravity
photons	$W^{\pm}$, Z^0	gluons	gravitons

Brief Introduction to Forces

Electricity Magnetism Weak Nucl. Strong Nucl. Gravity

Short range forces, significant only inside of the nucleus

Electromagnetism
photons

Weak Nucl.
$W^{\pm}$, Z^0

Strong Nucl.
gluons

Gravity
gravitons

Electroweak

Strong Nucl.

Gravity

We believe that the electromagnetic force and the weak force are two aspects of the same phenomenon even though the photon is massless and the W and Z are massive.

A Brief Introduction to Elementary Particles

3 charged leptons + 3 uncharged neutrinos

Generation	Particle	Mass
1	e	0.5 MeV
1	ν_e	~ 0
2	μ	106 MeV
2	ν_μ	~ 0
3	τ	1.78 GeV
3	ν_τ	~ 0

6 charged quarks

Generation	Particle	Mass
1	up	3 MeV
1	down	7 MeV
2	charm	1.3 GeV
2	strange	100 MeV
3	top	174 GeV
3	bottom	4.3 GeV

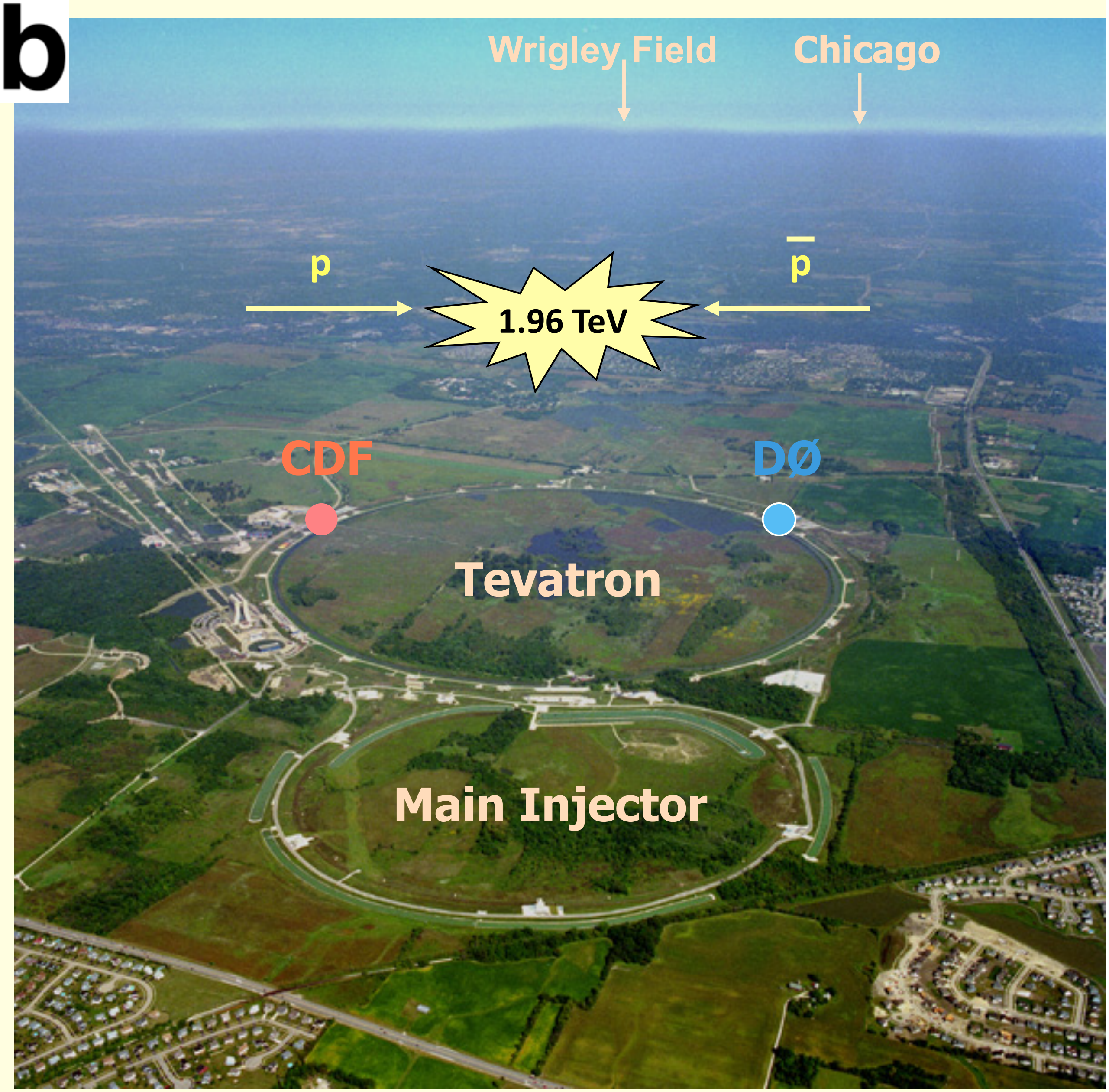
4 gauge (or force-carrying) particles

Name	photon	gluon	Weak Bosons	
Symbol	γ	g	$W^{\pm}$	Z
Mass	0	0	80 GeV	90 GeV

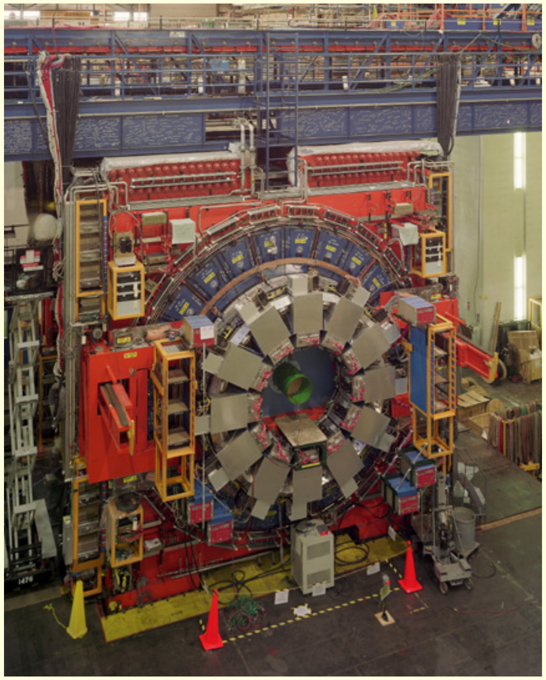
Fermilab

The Experimental High Energy Physics Group at Michigan State has been actively involved in research at the Fermi National Accelerator Laboratory in Illinois for the past 30 years.

Two large detectors are located at the 4-mile in circumference, and (almost) 2 Trillion Volt Tevatron Collider. They are called CDF and DØ.



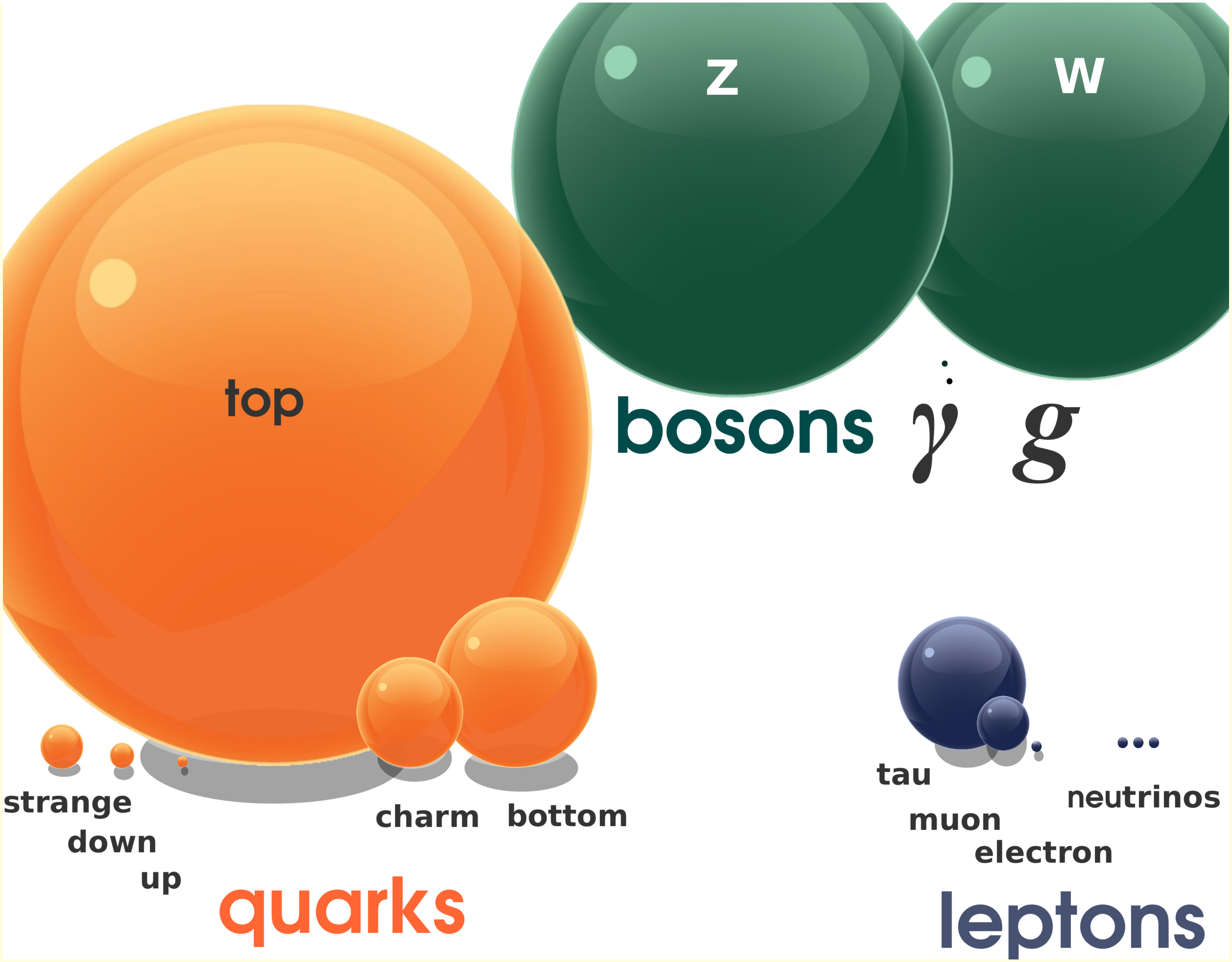
CDF and DØ



MSU is one of the few universities to participate in <u>both</u> of these large international collaborations.

Research at Fermilab has involved:-

- studies of quarks and gluons and their interactions (Quantum Chromodynamics)
- precision measurements of the W and Z bosons, the “heavy photons” that are the gauge particles for the weak force
- discovery and subsequent study of the (extremely massive) Top Quark


Z
W
top
bosons γ g
strange
down
up
charm
bottom
quarks
tau
muon
electron
neutrinos
leptons

Reasons for going to Higher Energy

- We want to probe the structure of matter at the smallest possible distance scale
  - Higher energy means shorter wavelength ($\lambda = h/p$)

- We want to search for new heavy particles
  - $E = mc^2$ implies that more **E** results in more **m**

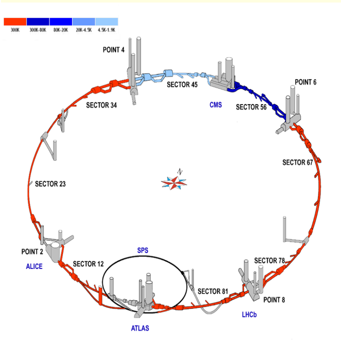
- The probability for producing even previously discovered particles (top and bottom quarks, W and Z bosons, etc) increases with energy
  - larger cross section ➔ more events ➔ precision studies

- Can we understand "electroweak symmetry breaking" i.e. why are the W and Z heavy while the photon is massless?
  - find the Higgs particle!

All of these require the highest energy that we can achieve

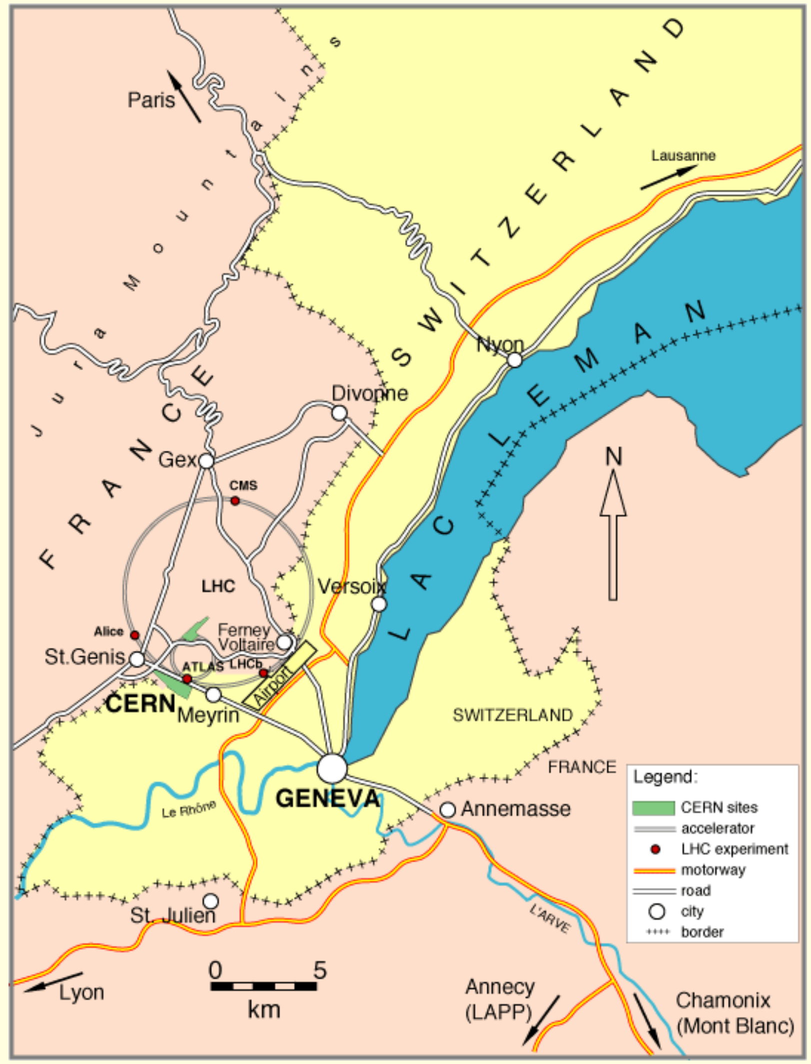
CERN, the LHC, and ATLAS

•CERN -- the European Center for Particle Physics



•LHC -- the Large Hadron Collider (a 7 TeV synchrotron)

•ATLAS -- one of four large detectors at the LHC



A Brief Explanation of Synchrotrons

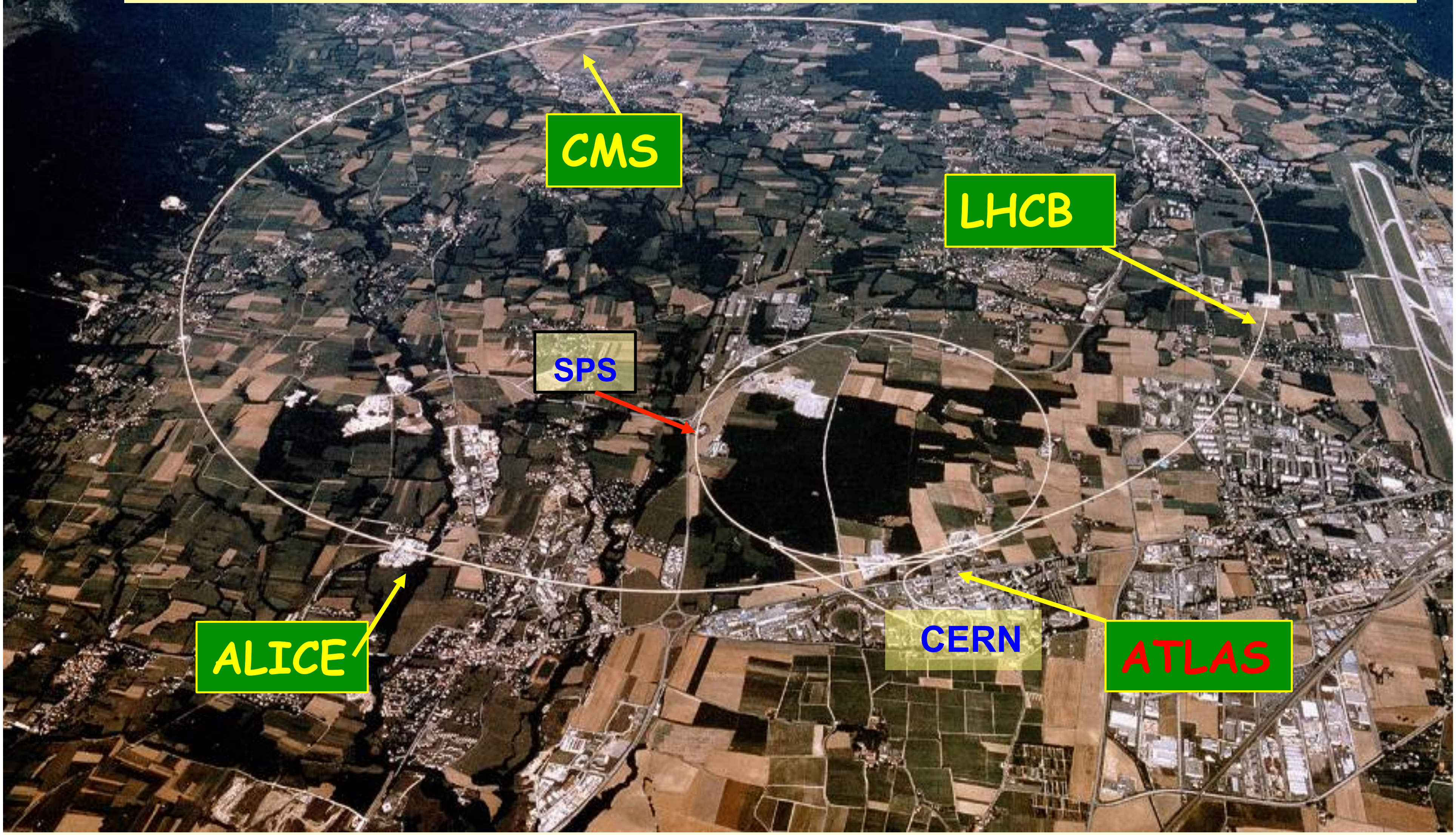
Reminder: 1 eV is the energy gained by a particle with a charge e = $1.6\text{x}10^{-19}$ C in traversing a potential difference of 1 Volt. ➔ 1 eV = $1.6\text{x}10^{-19}$ Joules.
[We also use MeV = million, GeV = billion, TeV = trillion]

A linear accelerator of 7 TeV would be ≈ 150 miles long and cost $75 billion. Instead we use a magnetic field to bend the protons into a circle, and reuse the same voltage source of 350,000 kV approximately 20 million times. The magnetic field is created by 1232 superconducting dipole magnets + numerous focusing and correction magnets.

As the particle energy rises, the magnetic field is increased to compensate and keep the proton in a circle.

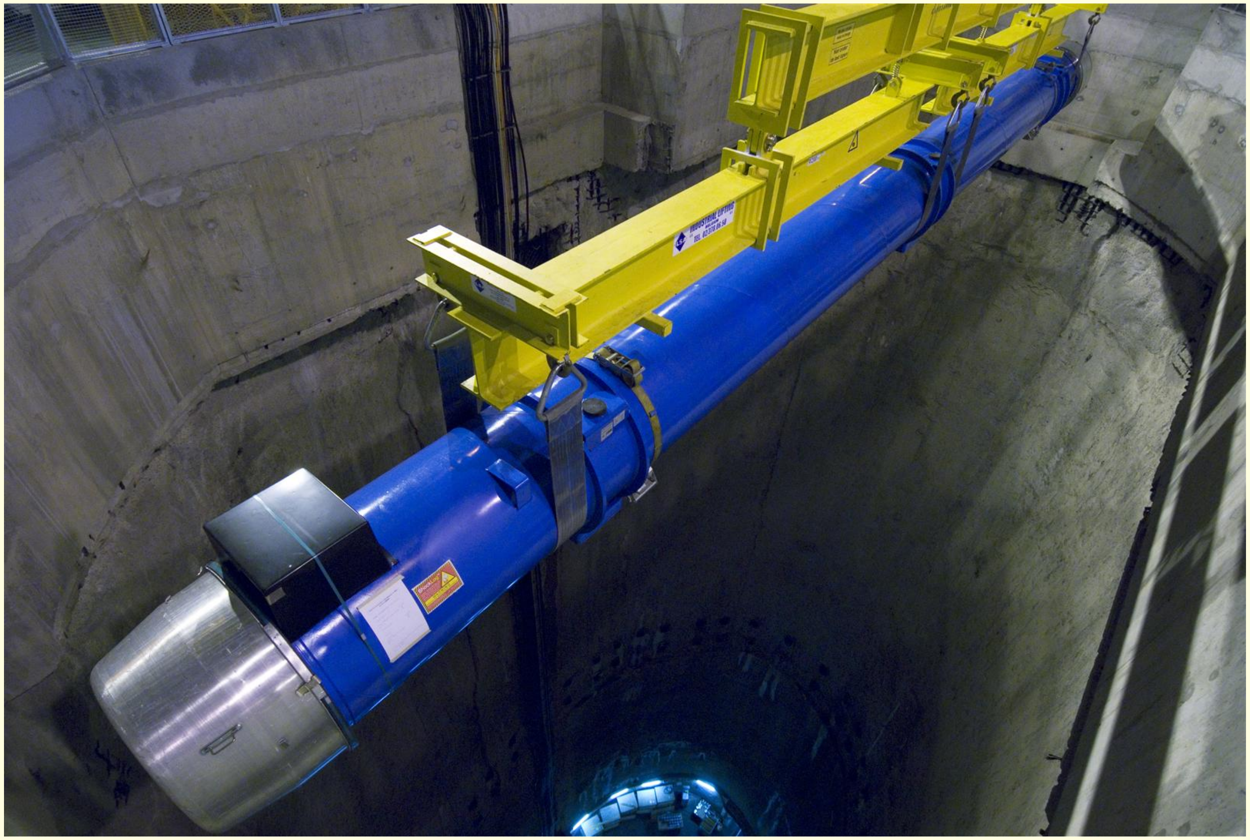
The Large Hadron Collider

26 km in circumference, 3000 superconducting magnets,
100 meters underground, stored energy of beam = 700 MJ

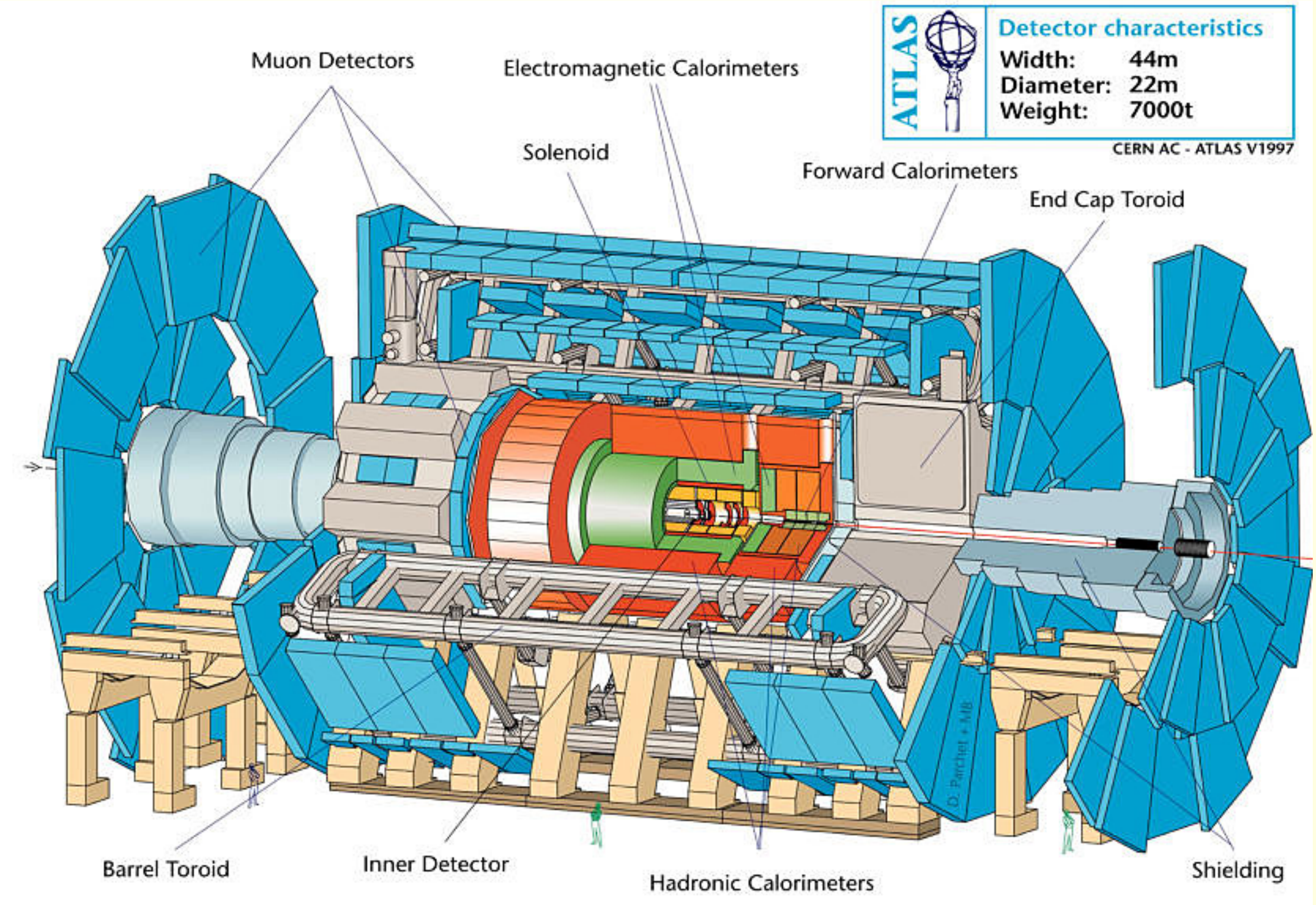


Superconducting Magnets

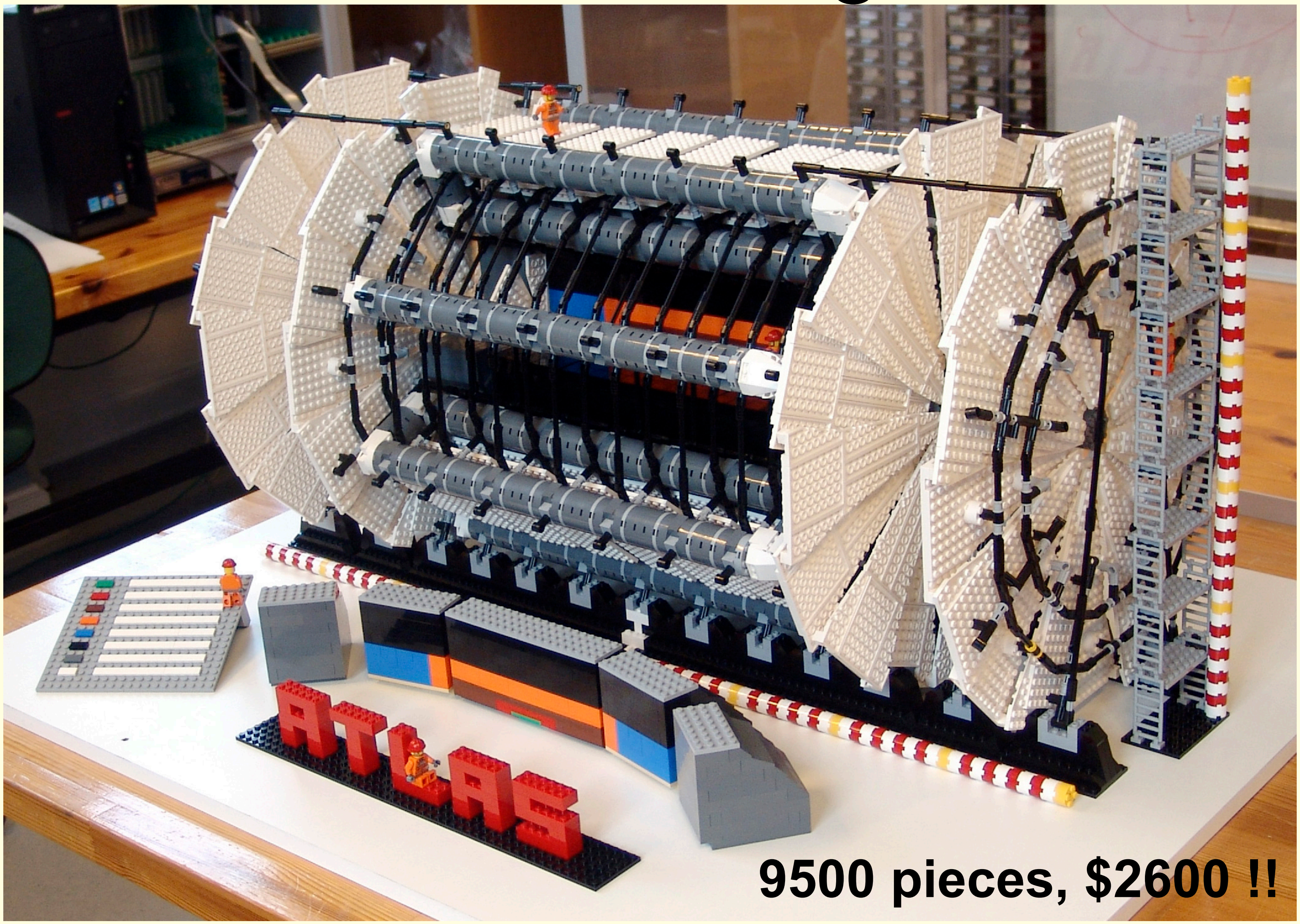
- 15 m long
- Zero resistance – a good thing!
- Magnetic field = 9 Tesla
- They have to be kept cold: around 1.9K
- Magnetic stored energy = 10 GJ



The ATLAS Detector

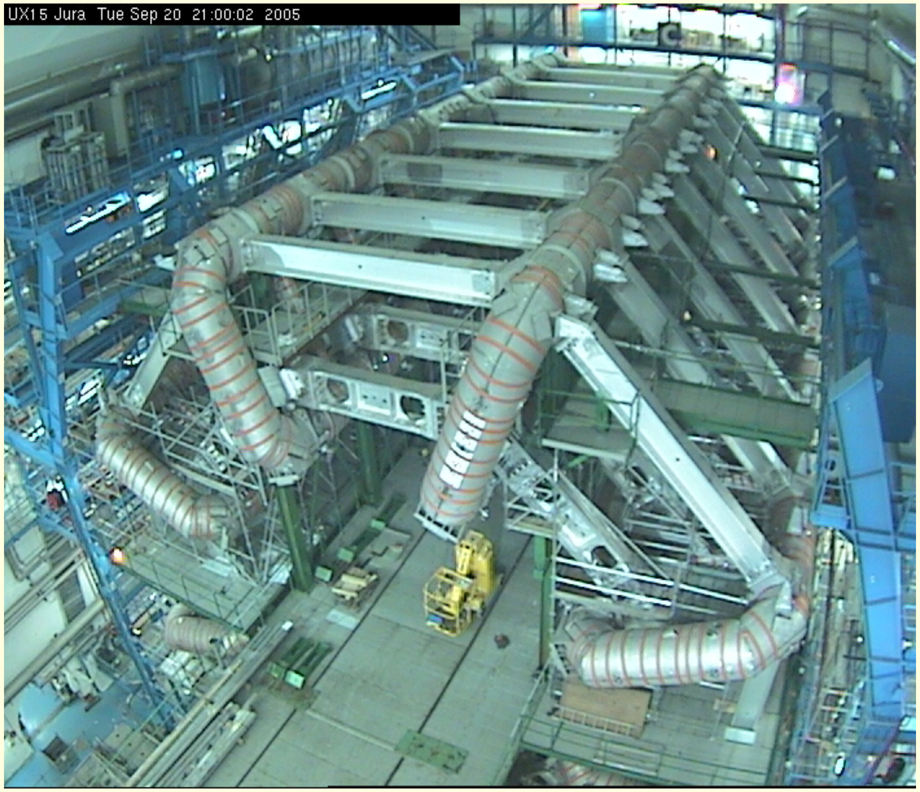


ATLAS in Lego!



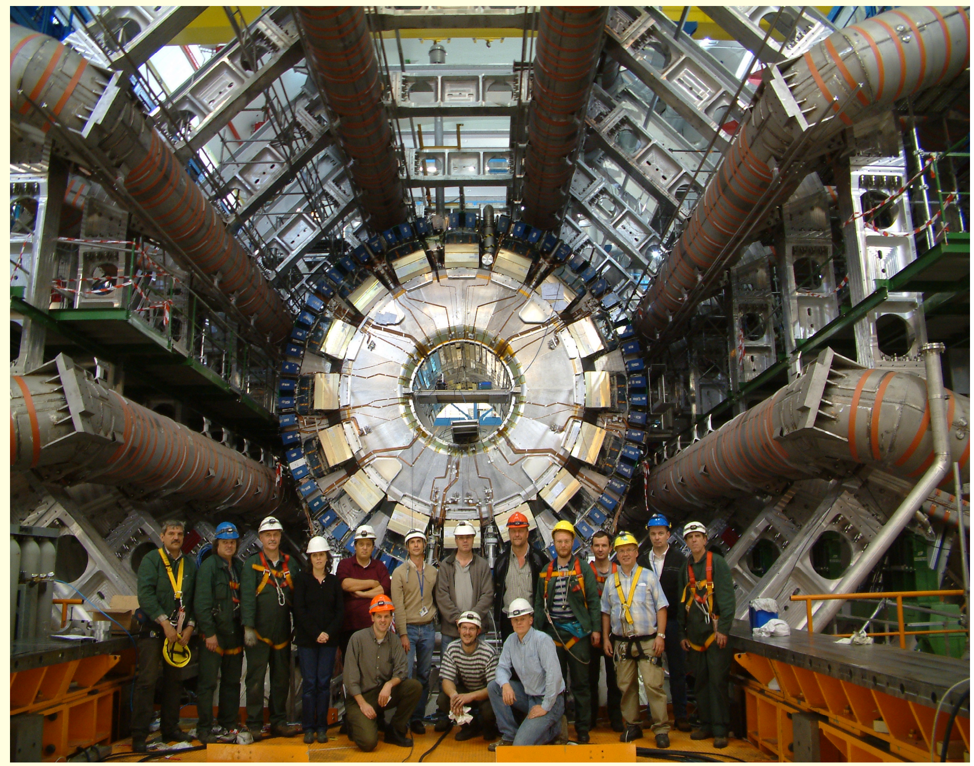
9500 pieces, $2600 !!

ATLAS Photos



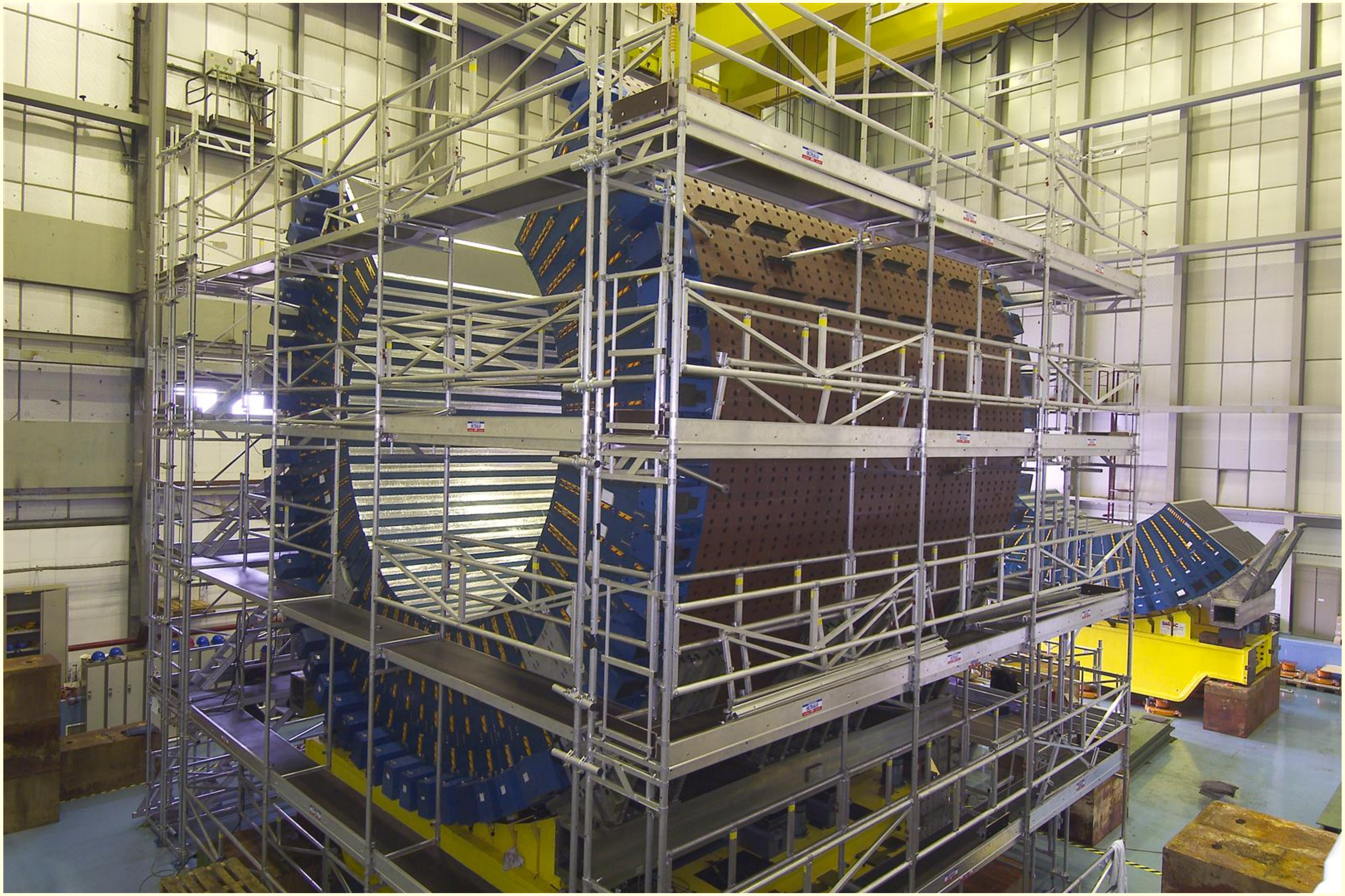
The superconducting toroid (8 coils in total)

The team responsible for inserting the calorimeter system inside the magnet. The central calorimeter, weighing approximately 2000 tons, is the silvery object behind the group. Many of the calorimeter modules were assembled at MSU.

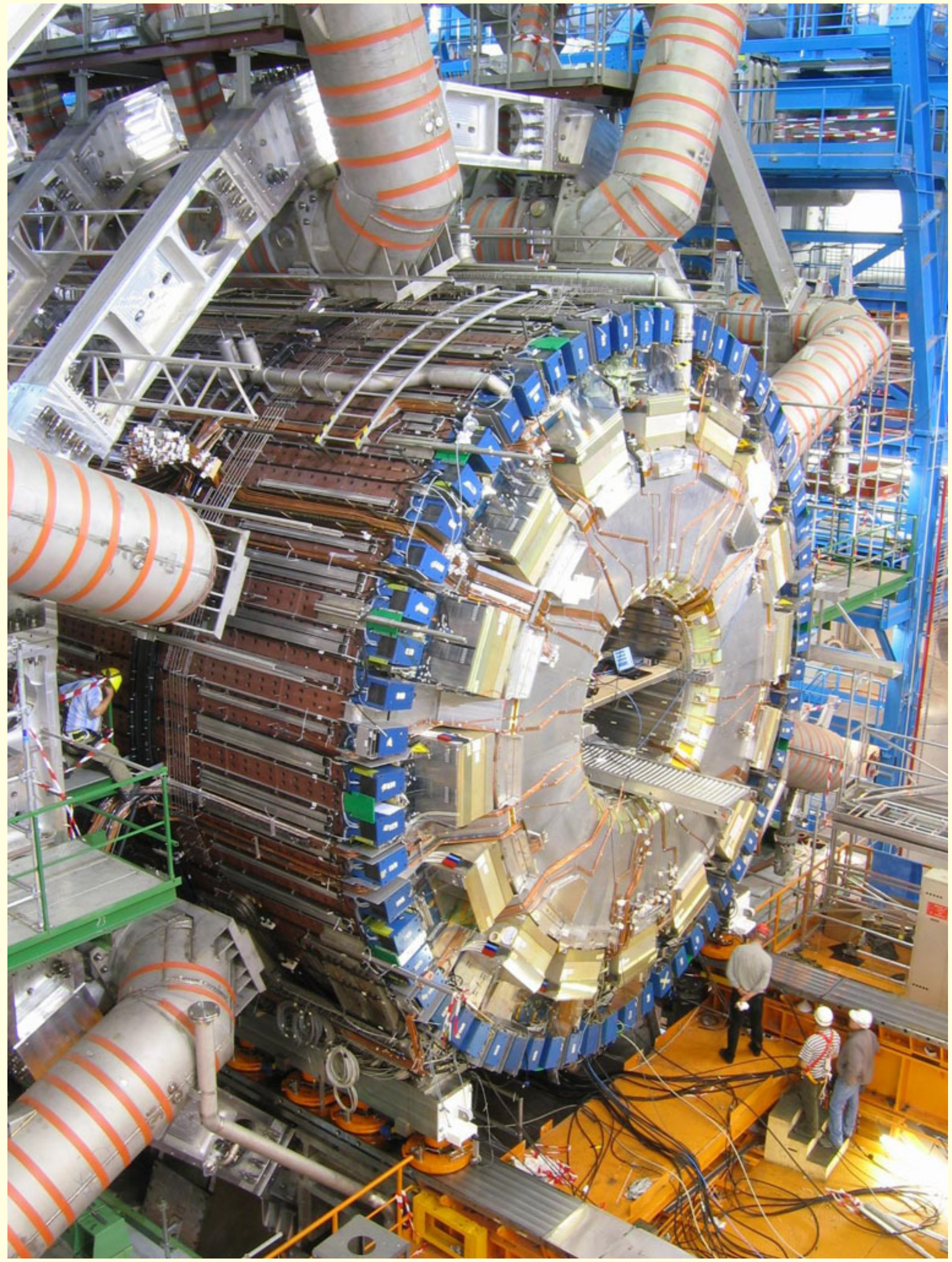


Tilecal modules arriving at CERN

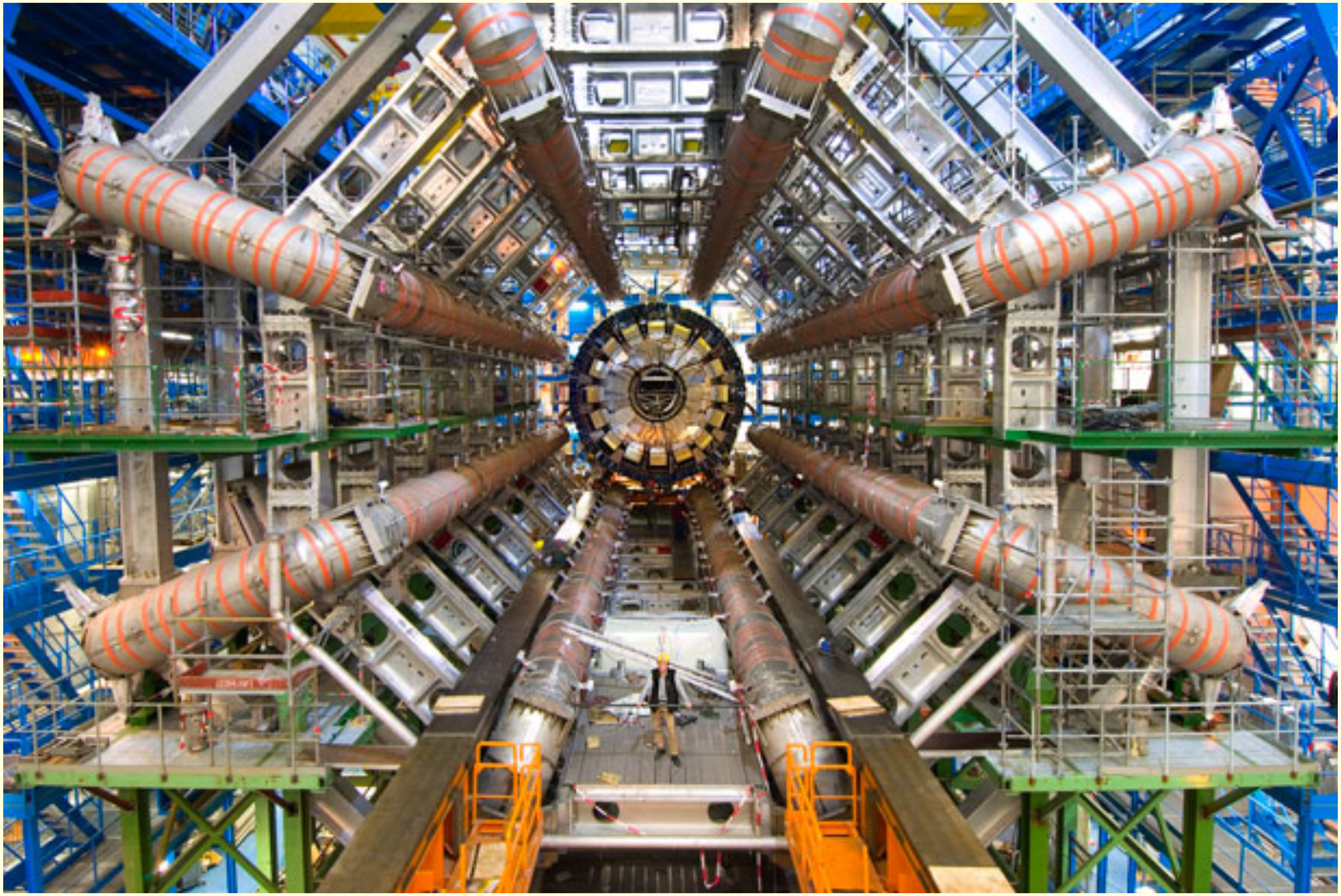
Tilecal being assembled



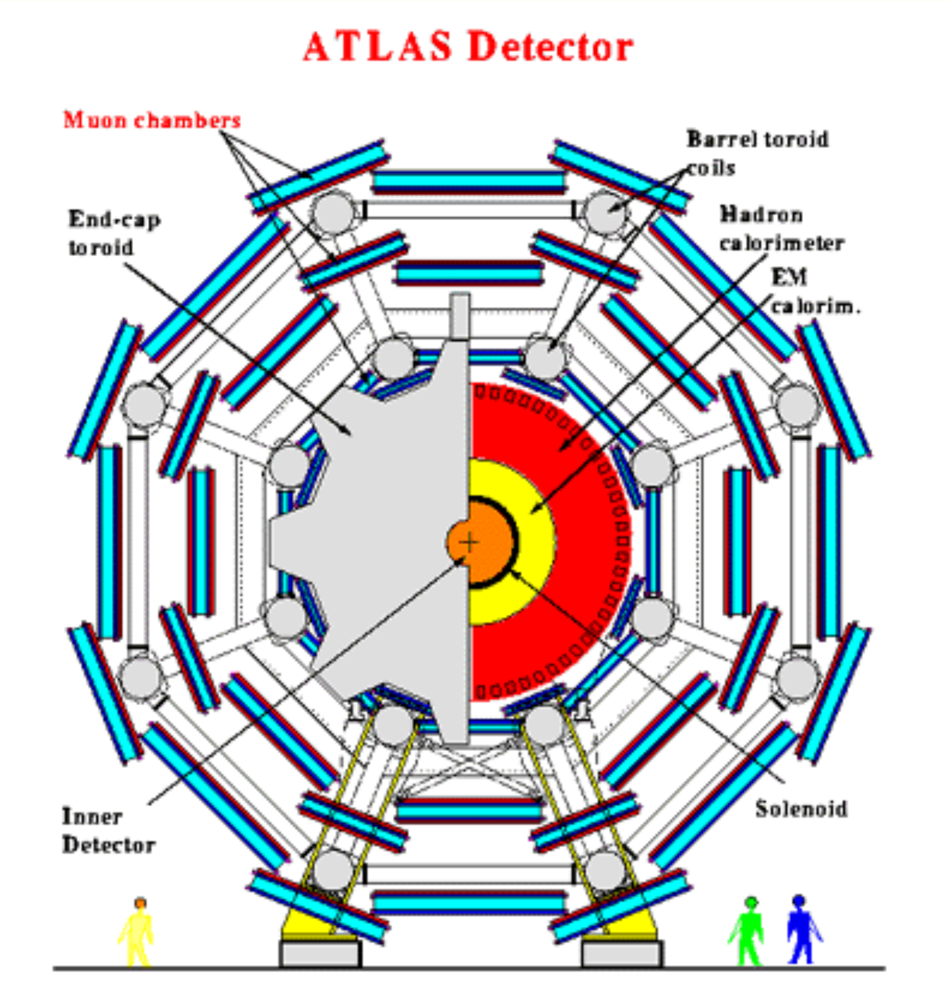
The Tile Calorimeter being installed inside the coils of the toroid magnet



The ATLAS Toroid



The ATLAS Muon Spectrometer



We would like to measure a 1 TeV muon momentum to about 10%.

Implies a sagitta resolution of about 100 µm.
over distances of ~10 m!

These very large, precision drift chambers were built by several of the collaborating institutes including the **University of Michigan**

The Muon *"Big Wheels"*

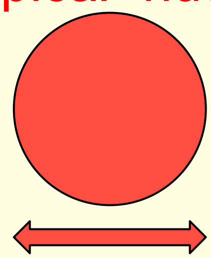
Collision Rates

- The LHC collides two beams of 4 TeV protons
- Each beam contains ~3×10^{14} protons
- Each proton takes ~90 μsec to travel the ~17 mile circumference, i.e. ~11,000 circuits/sec
- Beam size ~20 μm but protons are so small they mostly miss each other
- Collision rate is "only" 1×10^{9} Hz
- Most collisions involve "known" physics ==> need a trigger system to extract the interesting events

A Brief Explanation of Cross Section

From the first measurements of Ernest Rutherford it was realized that the probability of a nuclear reaction is related to the area of the nucleus.

"Typical" nucleus



10^{-12} cm

Area = 10^{-24} cm^2 = 1 barn

"as big as the side of a barn"

A proton has a cross sectional area of approximately 7×10^{-26} cm^2 and so a total "cross section" of σ = 70 mbarns.

The likelihood of a specific result of a collision eg producing a W boson is much less, but still quoted as a cross section, for example, σ_W = 50 nb

A Brief Explanation of Luminosity

The number of collisions (or interactions) depends on the number of protons squeezed into the small area of each beam, and the size of each proton. We express this (confusingly!) as an inverse area.

Instantaneous Luminosity is (typically) about $3\mathrm{x}10^{33}$ cm^{-2} s^{-1}

Total Luminosity in 2011 was 5.4 fb^{-1}

This system has the advantage that the number of collisions, or expected events, or particles produced, can be found by multiplying the luminosity ($\mathcal{L}$) and the cross section (σ).

For example:-

Number of collisions per second = $\mathcal{L}\sigma = 3\mathrm{x}10^{33} \mathrm{~x~} 7\mathrm{x}10^{-26}$

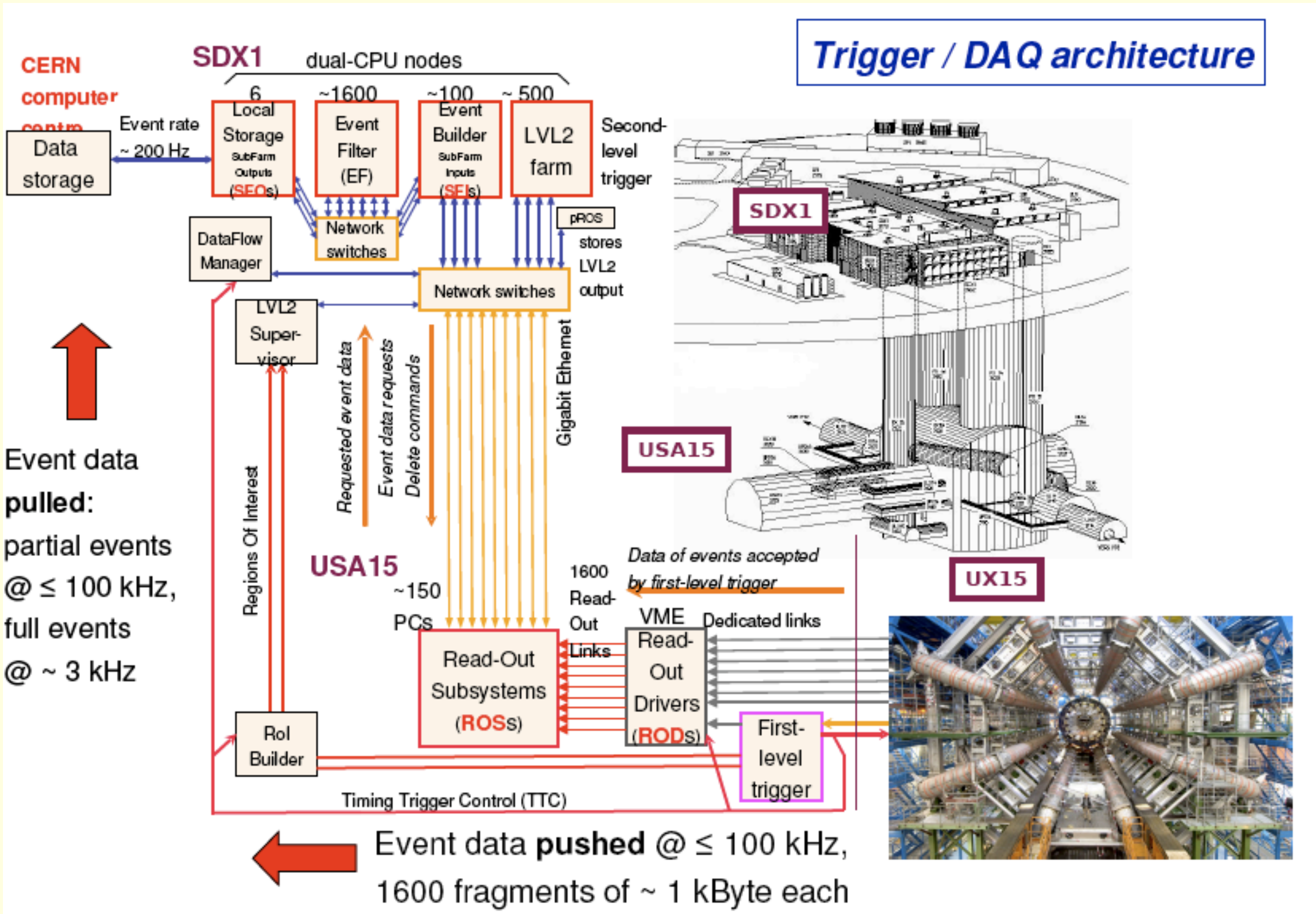
≈ 200 million per sec

Total # of collisions in 2011 = 5.4 fb^{-1} x 70 mb ≈ 400 trillion

# of W's produced in 2011 = 5.4 fb^{-1} x 50 nb ≈ 270 million

ATLAS Trigger/DAQ

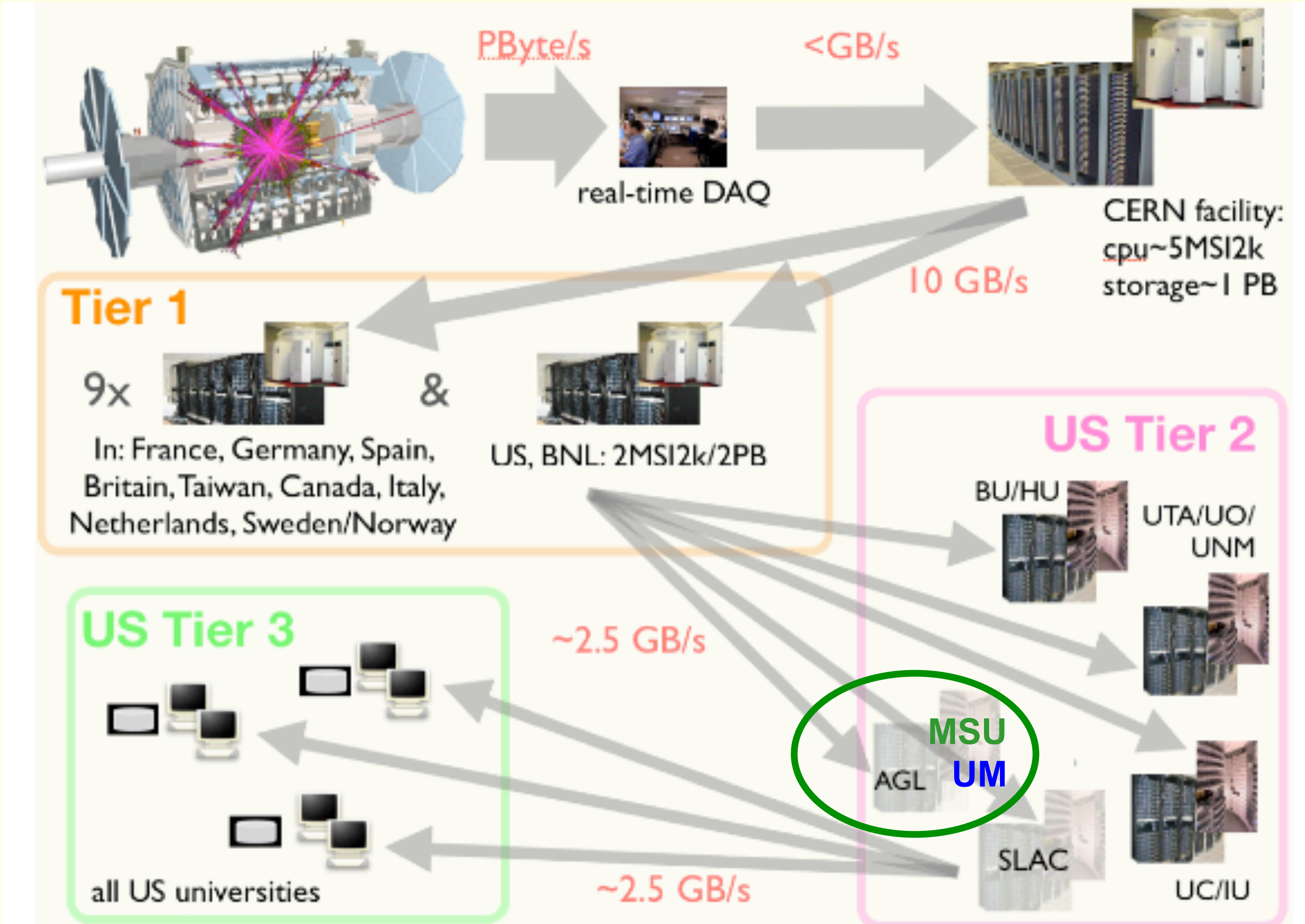
•Our MSU group has been involved in designing and building the complicated fast electronics and computers that make up the trigger and data acquisition system (TDAQ) for ATLAS.



Here is a picture of some of us working hard at CERN!

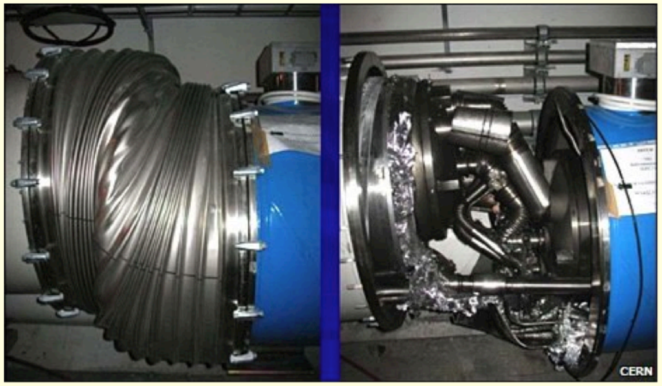
The MSU group in residence at CERN presently consists of one professor, five postdocs, one graduate student and one engineer. Many more during the summer!

ATLAS Computing



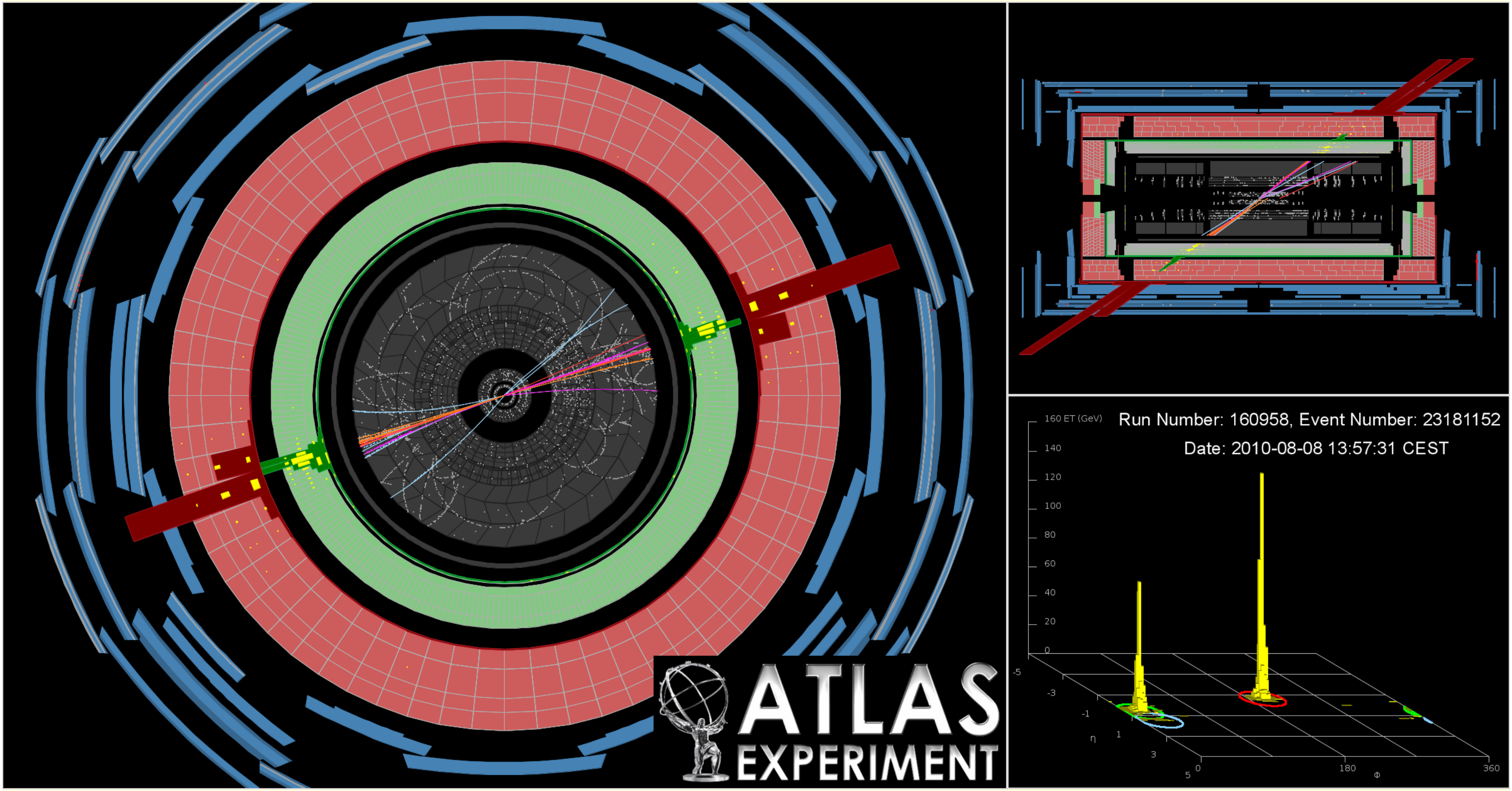
History of the LHC

- MSU joined the ATLAS collaboration in 1996.
- The first beams were recorded in September 2008.
- Ten days later, an electrical fault between 2 magnets caused a quench and helium release – 57 magnets were damaged.

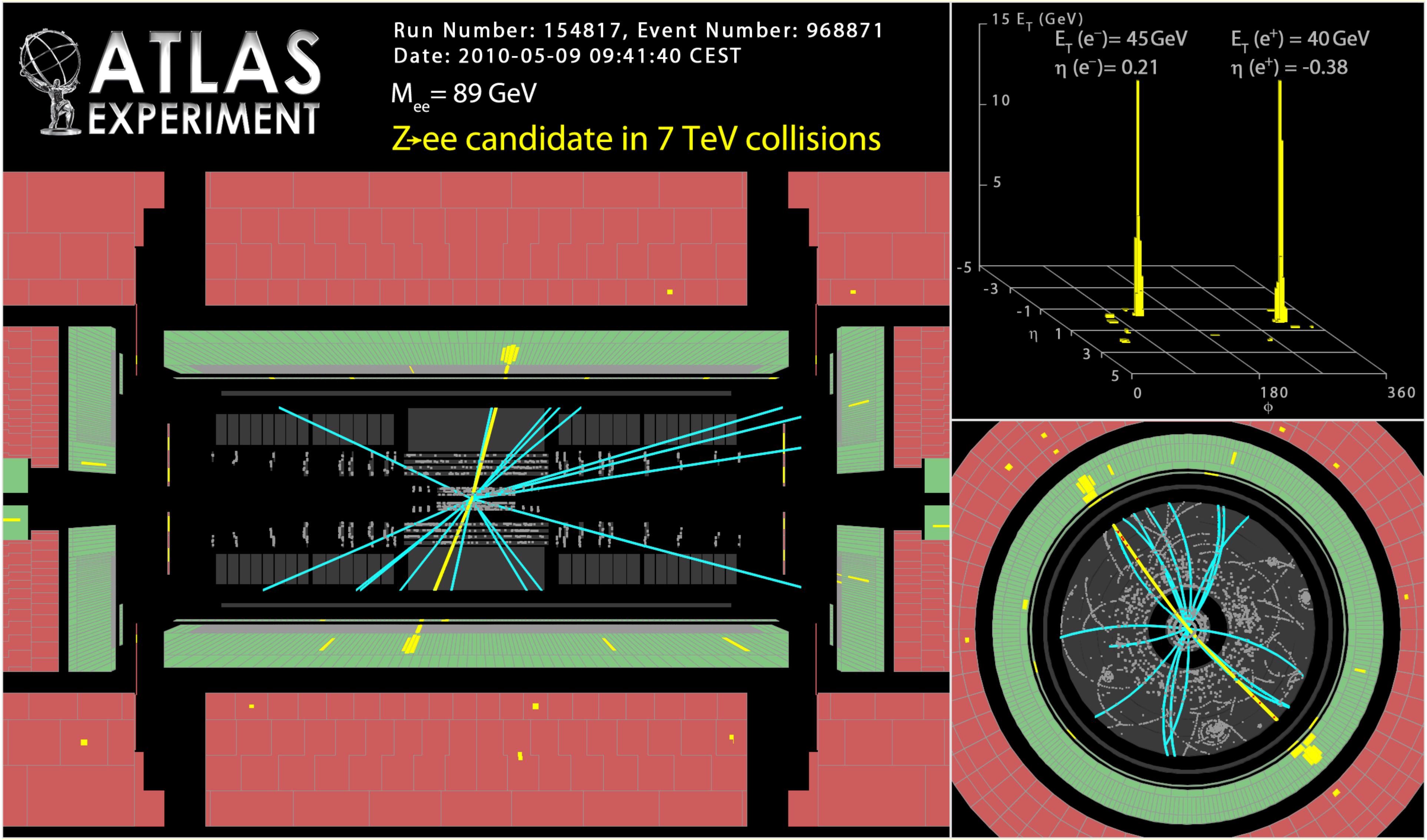


- The LHC resumed operations in December 2009 with a "conservative" energy of 3.5 TeV x 3.5 TeV.
- 3.2 trillion collisions were recorded in 2010.
- 370 trillion collisions were recorded in 2011.
- This year the energy has been raised to 4 TeV x 4 TeV and, so far, 1540 trillion collisions have been recorded.

What do these collision events look like?



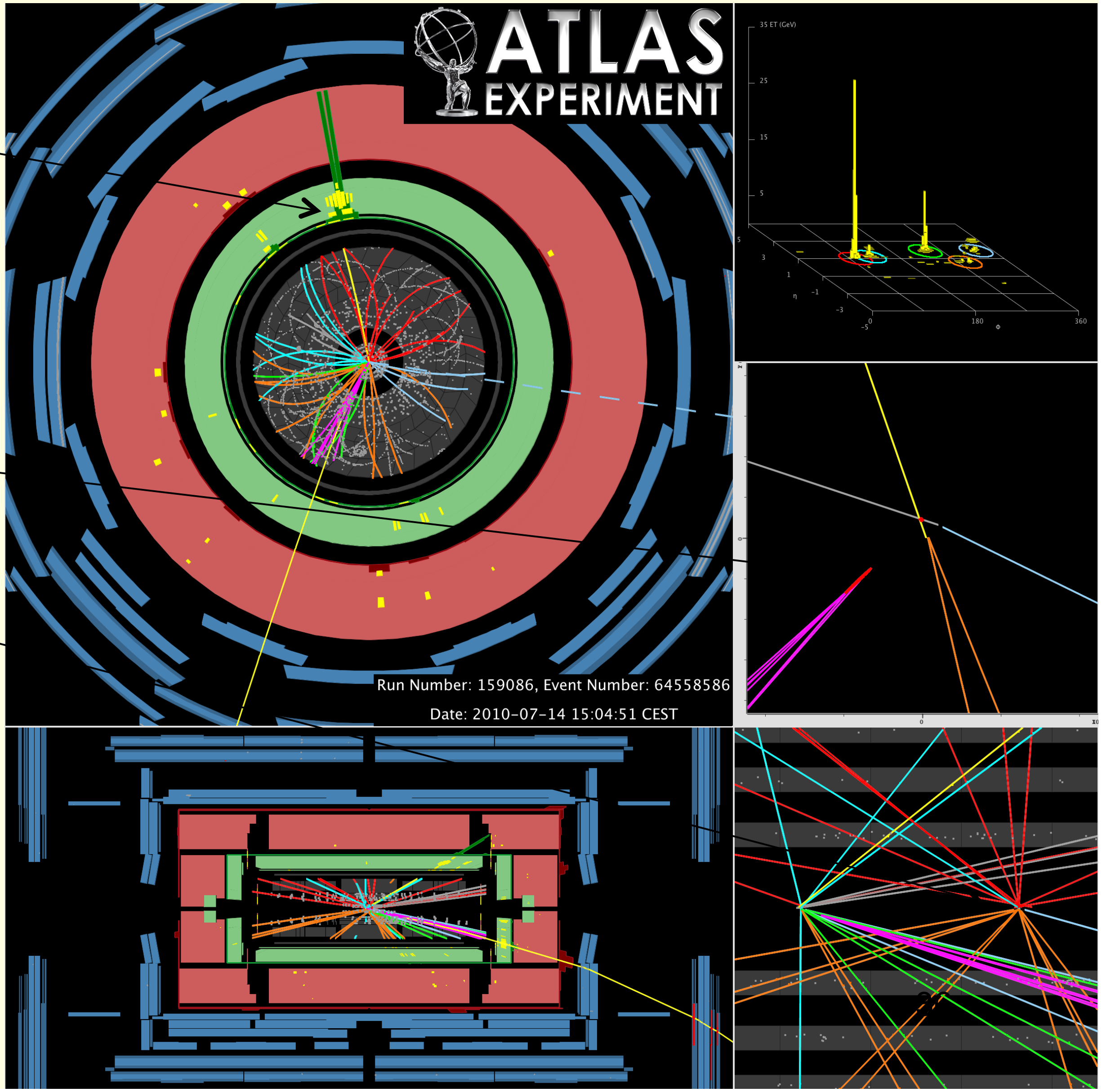
A typical 2-jet event

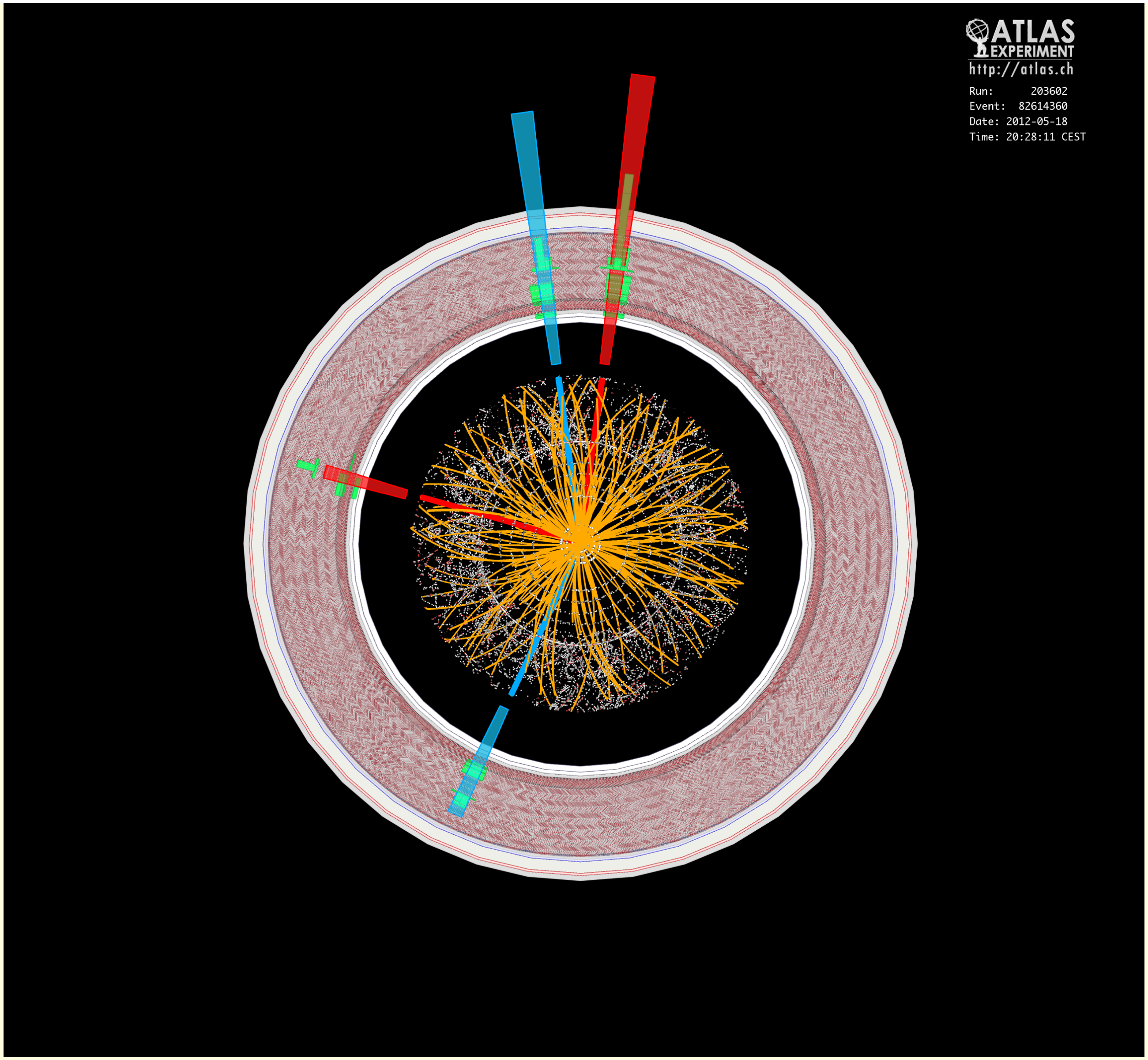


A Z^0 decaying into 2 electrons

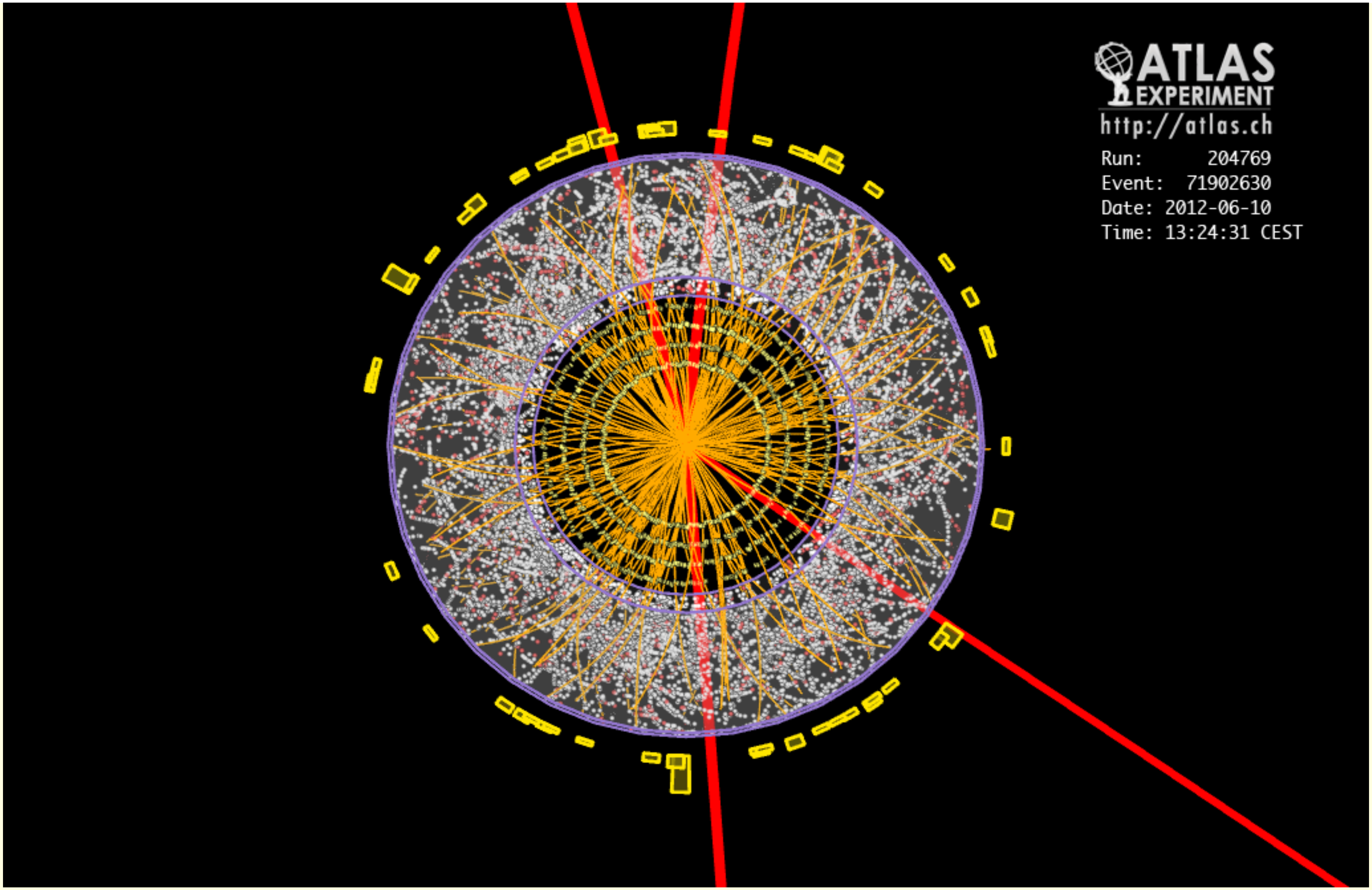
A top quark

- Electron + jets event
- Secondary vertex tagged jet
- Extra pileup interaction

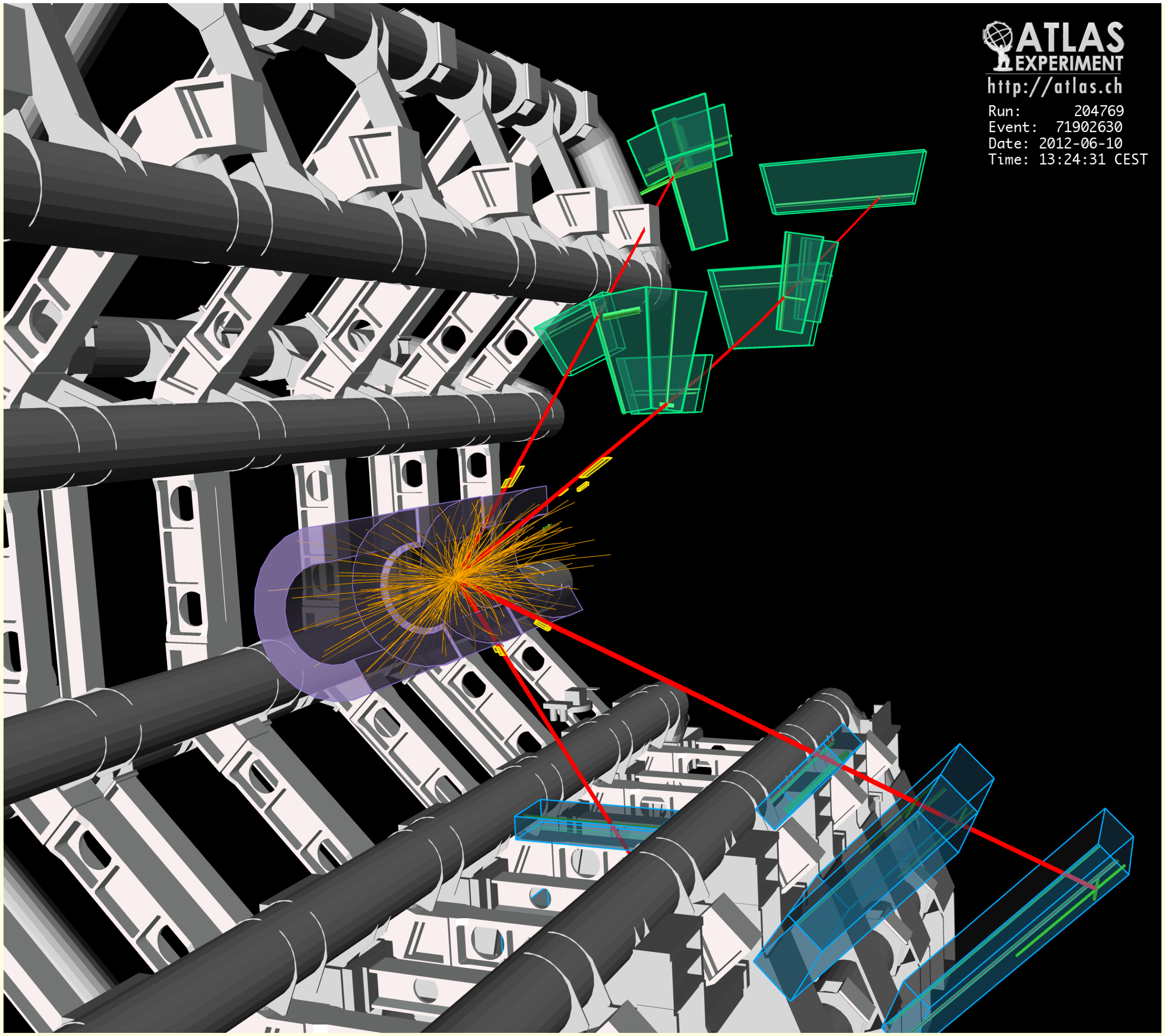




A Higgs boson decaying into 4 electrons



A Higgs boson decaying into 4 muons



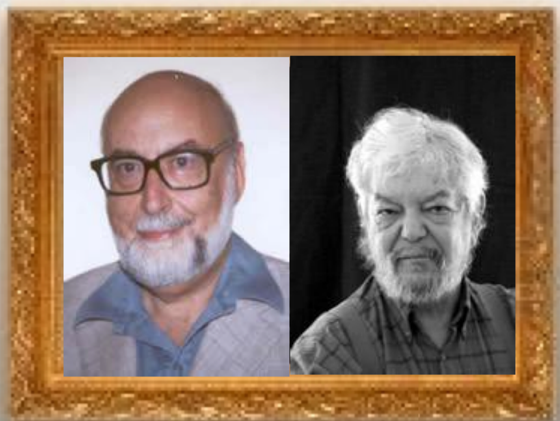
The same event in 3-dim showing the muon chambers

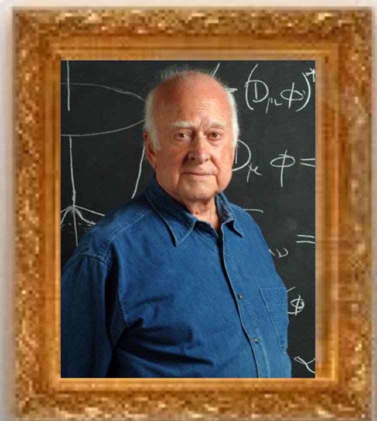
The Higgs Mechanism

- Perhaps the prime (but not the only!) objective of the LHC is to understand the mechanism of symmetry breaking – if the weak force and the electromagnetic force are just two aspects of the same Electroweak Interaction, why are the W and Z bosons so massive while the photon is massless?
- A possible solution was suggested in 1964.
- The universe is filled with a quantum field, called the Higgs field, that interacts with particles giving them their mass.
- The quantum of the Higgs field is the Higgs boson. Its mass is not predicted.
- Its observation is complicated by a variety of production processes and, depending on its mass, several different decay modes.

2010 Sakurai Prize

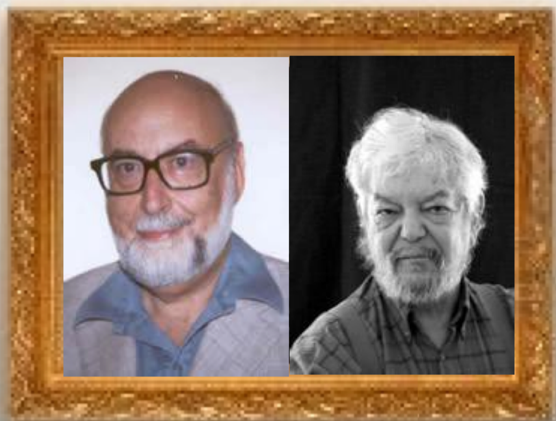
... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."

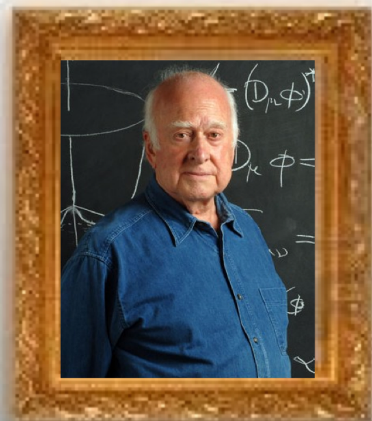




2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."





Englert Brout Higgs Guralnik Hagen Kibble

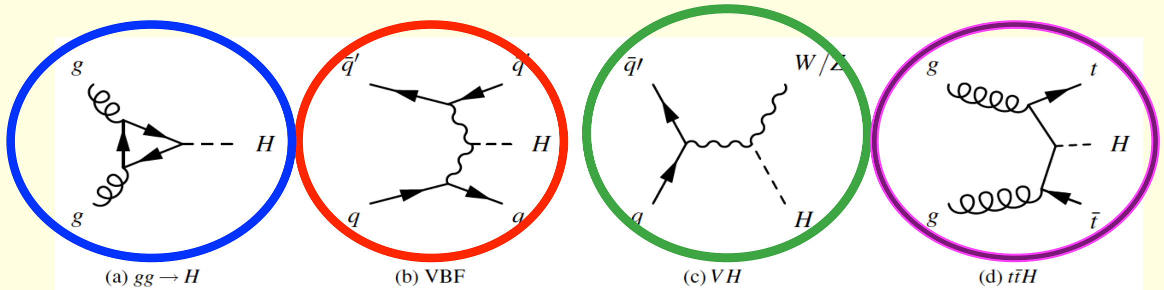
– PRL 13, 321323 (1964)

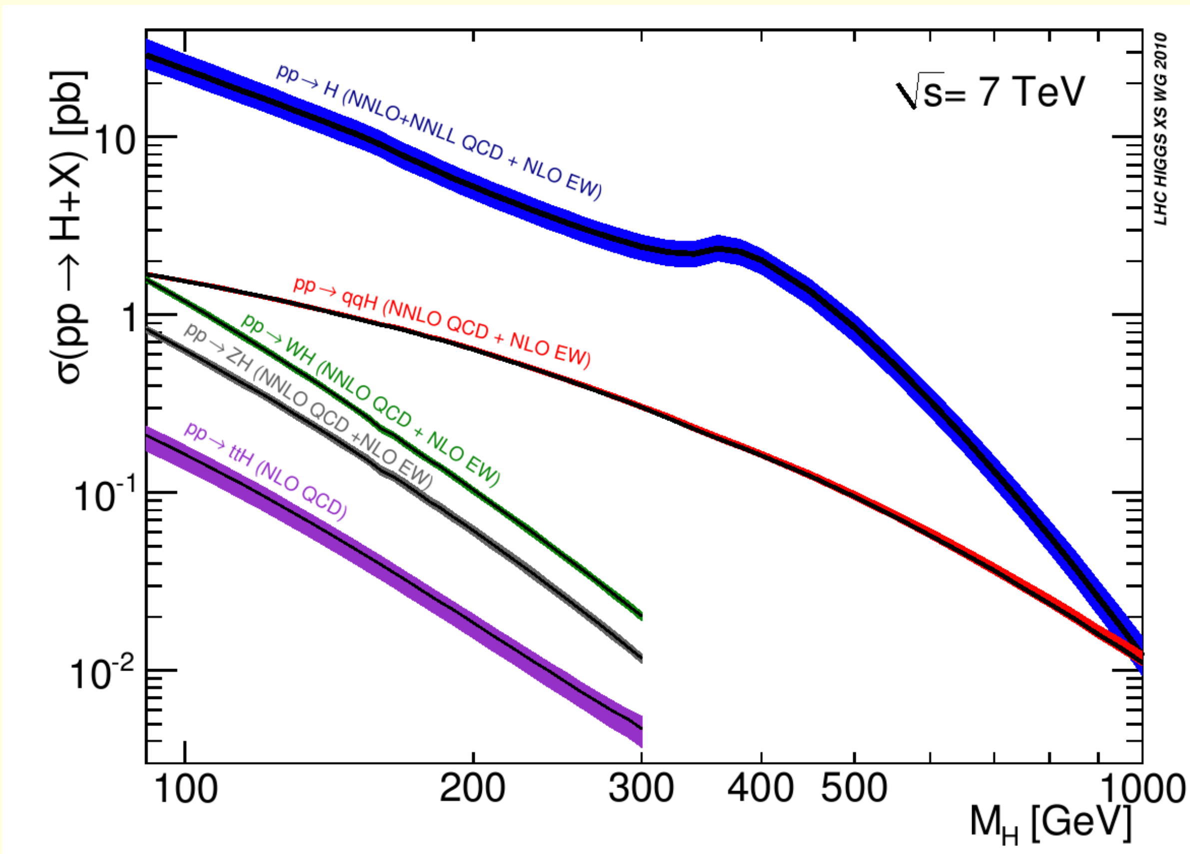
– PRL 13, 508509 (1964)

– PRL 13, 585587 (1964)

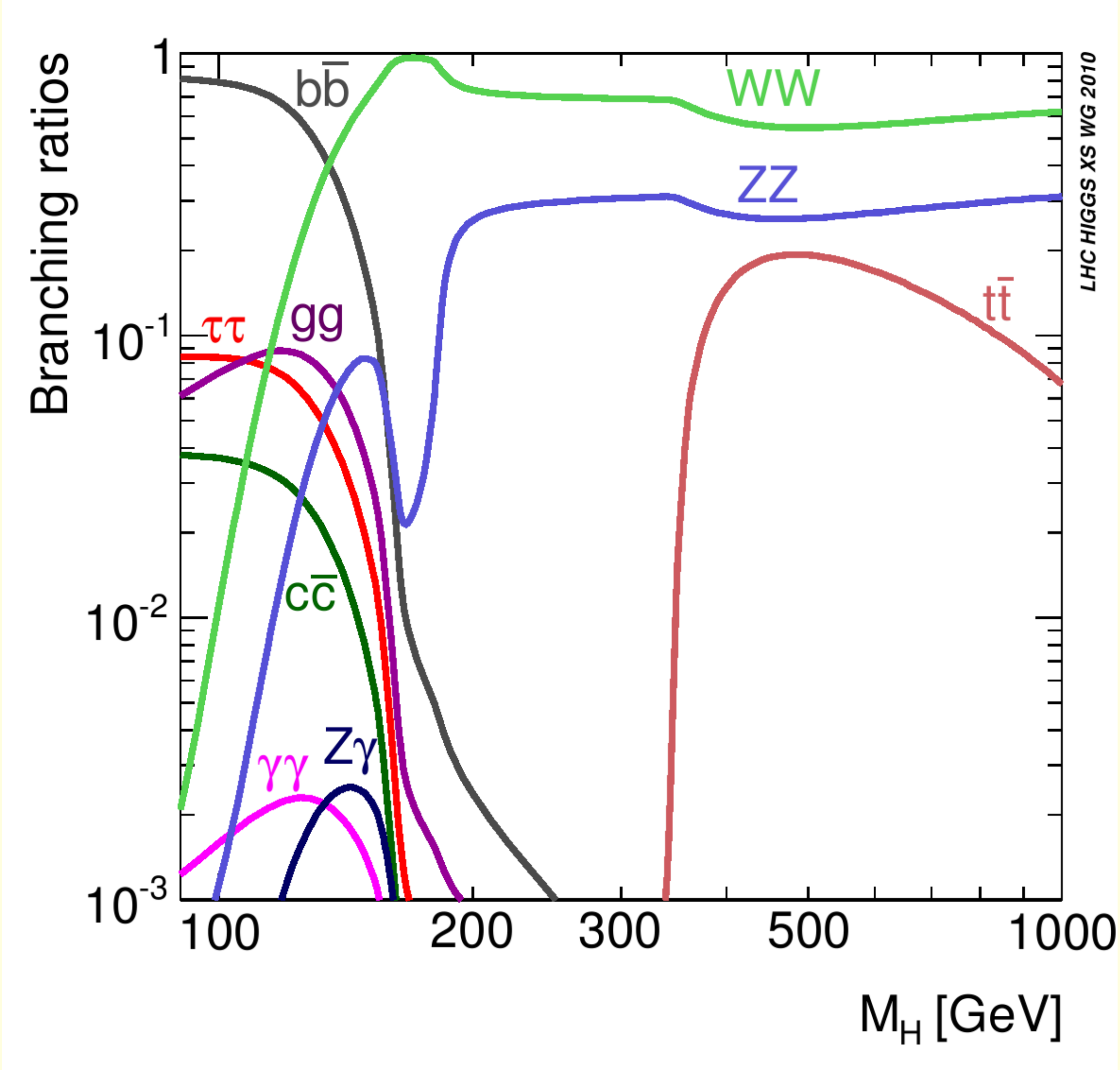
Disclosure: Though we often refer to the Higgs mechanism/boson, we're really discussing the BEGHHK mechanism/boson.

Higgs Production Processes



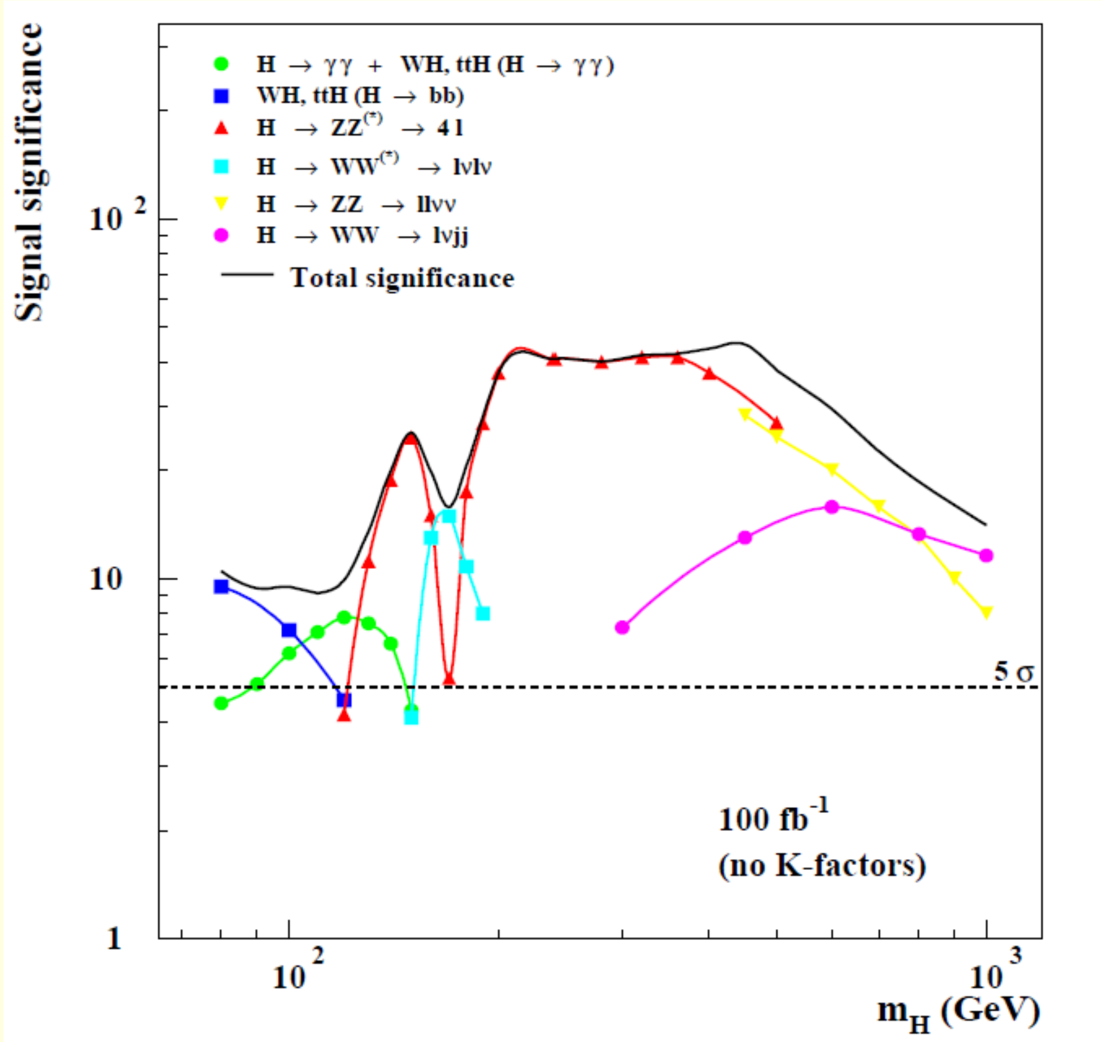


Higgs Decay Processes



Combining all Higgs Channels

- If there is a Higgs boson, ATLAS will find it with a few years' data, no matter what its mass is
- For most of the mass range, we will see the Higgs in multiple channels
  - We can start probing its couplings: it looks like a Higgs, but does it act like a Higgs?
- The other large experiment, CMS, has comparable sensitivity



The Higgs Boson

The results on Standard Model (SM) Higgs searches by ATLAS were presented at the International Conference on High Energy Physics held in Melbourne, Australia on July 4 - 11. The Higgs boson is predicted to decay into several decay channels. The most sensitive channels are:-

$H \rightarrow \gamma\gamma$

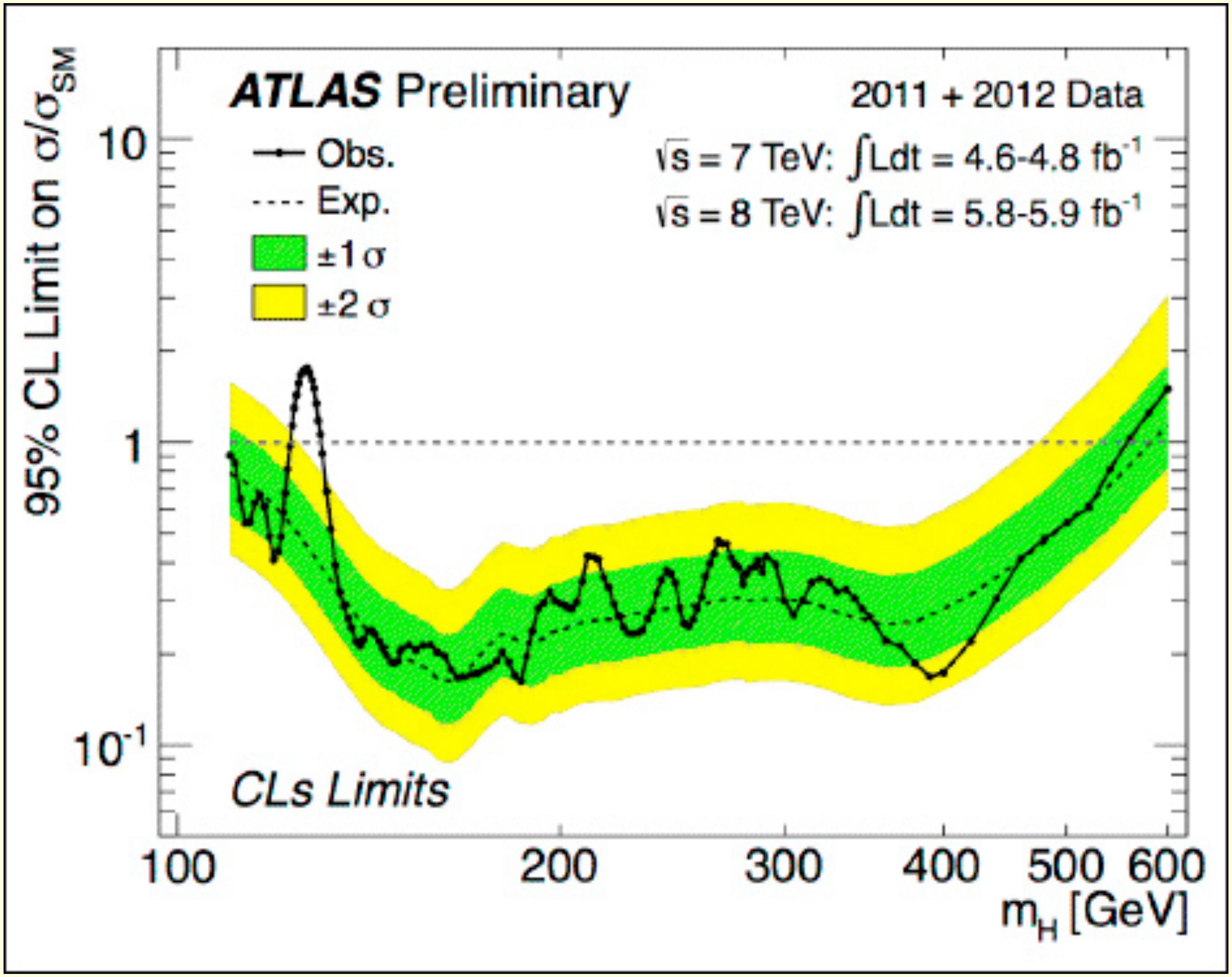
$H \rightarrow ZZ \rightarrow$ 4 charged leptons

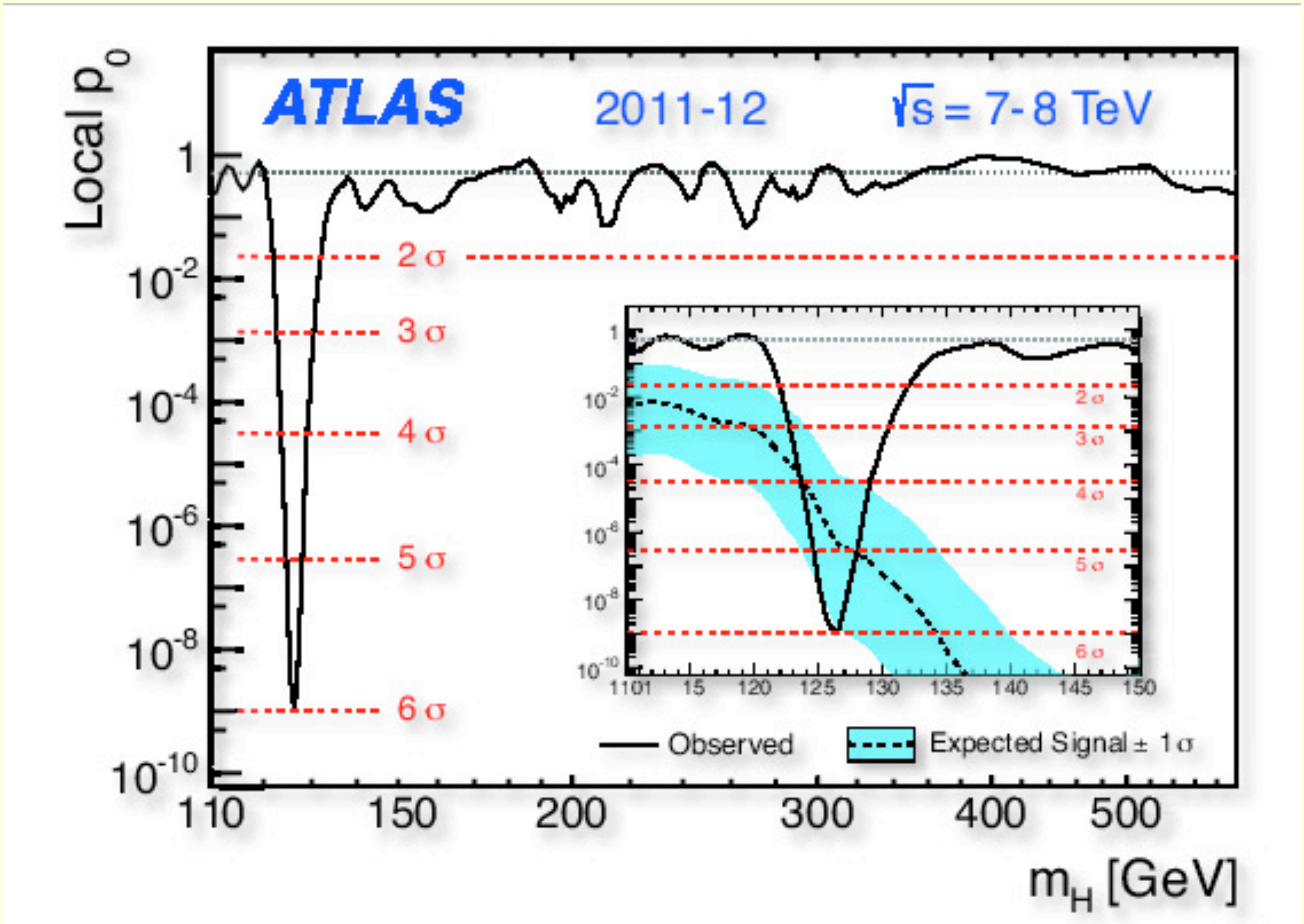
$H \rightarrow WW \rightarrow$ 2 charged leptons + 2 neutrinos

The results have just been submitted for publication and are essentially unchanged from those presented at the conference, and the overall conclusion also remains the same.

"We observe clear signs of a new particle with a mass around 126 GeV . We know that it must be a boson, the heaviest yet found. Our next step is to examine all of the properties of this new particle and see if they are consistent with the predicted Higgs boson."

Latest Higgs Result from ATLAS





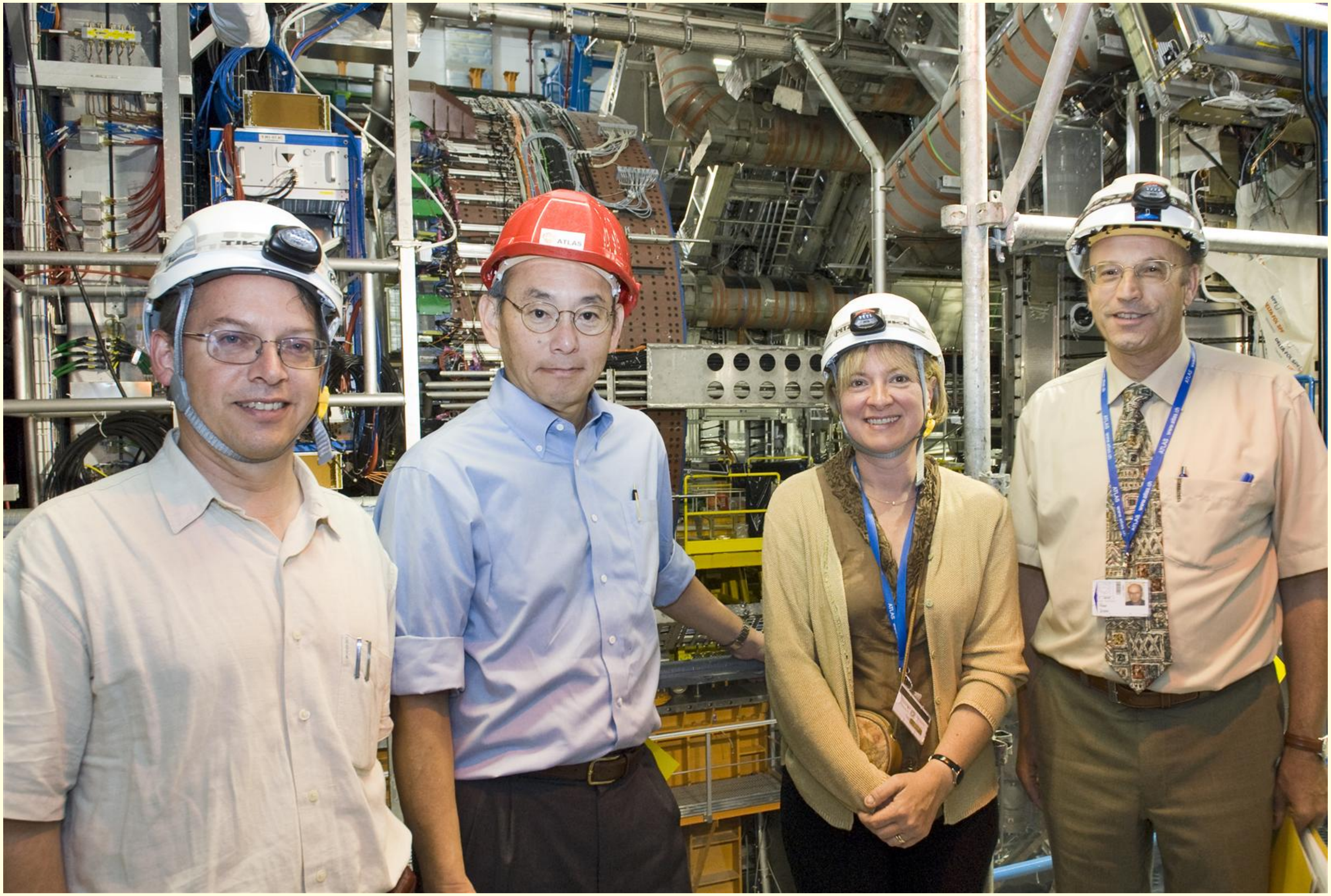
ATLAS
2011-12
√s = 7-8 TeV
Local p0
1
10-2
10-4
10-6
10-8
10-10
2 σ
3 σ
4 σ
5 σ
6 σ
110
150
200
300
400
500
mH [GeV]
Observed
Expected Signal ± 1σ

Already Observed at ATLAS

Peter Higgs

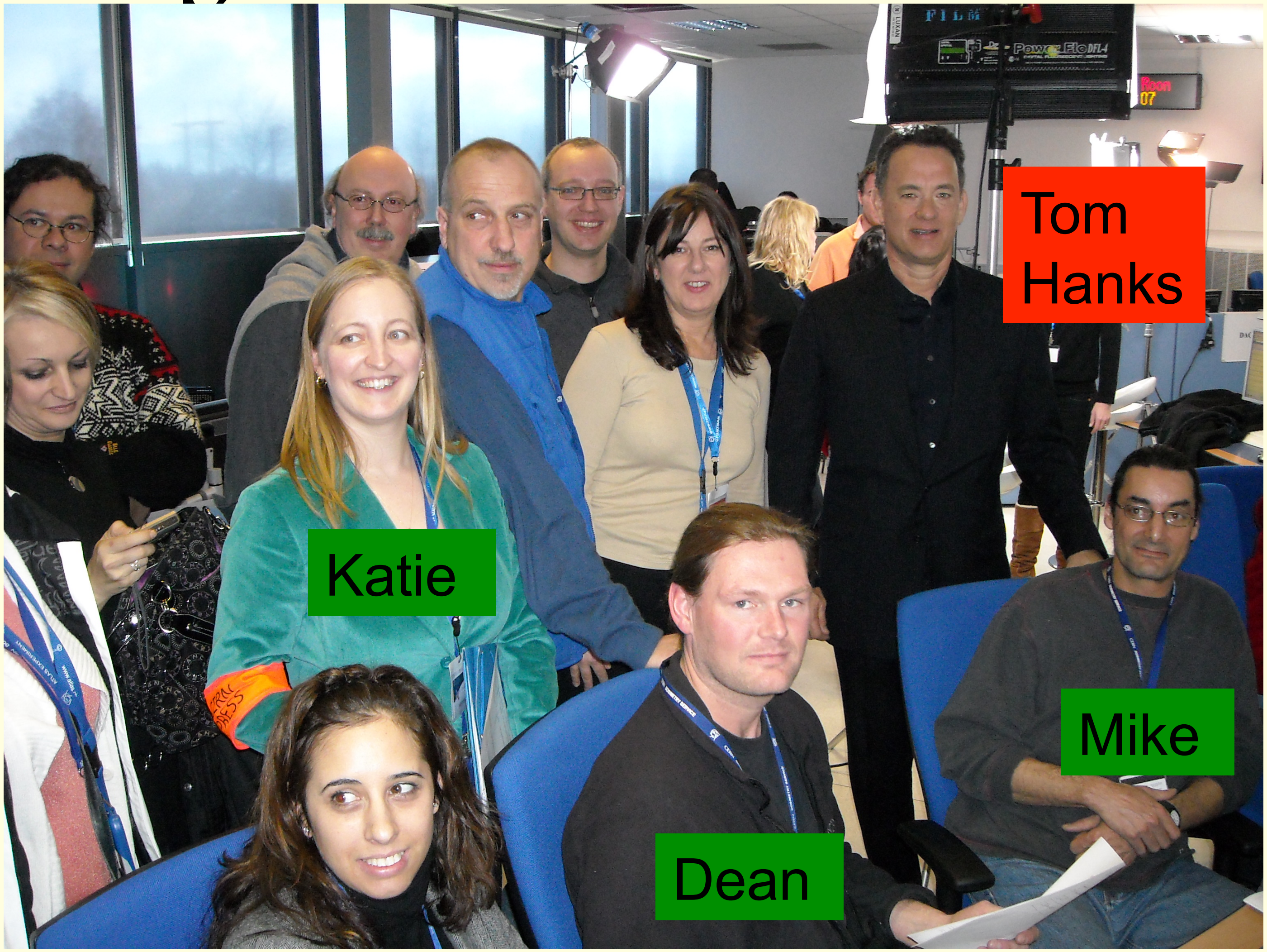
Other Visitors to ATLAS

Stephen Hawking



Steven Chu

Angels&Demons at CERN



In the ATLAS Control Room

The Muppets at CERN!

The Muppets (Dr Bunsen Honeydew, far left) visit the ATLAS detector at CERN during The Muppet Movie. Beaker, Bunsen's assistant, is absent due to being sucked up a vacuum tube.

Image courtesy Walt Disney Studios.

Some web sites

• CERN	public.web.cern.ch
• The LHC	lhc.web.cern.ch/lhc/
• ATLAS	www.atlas.ch
• US/LHC	www.uslhc.us/
• US/ATLAS	www.usatlas.bnl.gov/
• MSU ATLAS	www.pa.msu.edu/hep/atlas
• Bernard Pope	www.pa.msu.edu/people/pope